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AN INVESTIGATION OF VARIOUS PARAMETERS WHICH MAY AFFECT THE MIXED LAYER DEPTH IN THE OCEAN.

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# NAVAL POSTGRADUATE SCHOOL
## Monterey, California

# THESIS

AN INVESTIGATION OF VARIOUS PARAMETERS
WHICH MAY AFFECT
THE MIXED LAYER DEPTH IN THE OCEAN

by

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An Investigation of Various Parameters Which May Affect

the Mixed Layer Depth in the Ocean

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## ABSTRACT

A theoretical model is developed for making computerized forecasts of mixed layer depth. An empirical equation relating significant wave height to layer depth is used to account for mechanical mixing. Heat exchange parameters are introduced into the model to produce convective mixing. The u and v components of surface current are used to investigate the effect of convergence and divergence. The layer depths forecast by the model are compared to actual layer depths and to the Fleet Numerical Weather Central layer depth analysis.

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| | | |
|---|---|---|
| $A_n$ | - | solar altitude at noon |
| BT | - | bathythermograph |
| C | - | cloud cover |
| CH | - | combined wave height |
| CONV | - | convergence |
| $C_p$ | - | specific heat of sea water |
| DIV | - | divergence |
| E | - | Ocean Station Vessel ECHO |
| $e_a$ | - | vapor pressure of air |
| $e_w$ | - | saturated vapor pressure |
| FNWC | - | Fleet Numerical Weather Central |
| H. E. | - | heat exchange |
| $h_o$ | - | initial layer depth |
| $H_{1/3}$ | - | significant wave height |
| $K_1, K_2$ | - | constants |
| L | - | grid length |
| LD | - | layer depth |
| $L_t$ | - | latent heat of vaporization |
| $M_c$ | - | convective mixing factor |
| MLD | - | mixed layer depth |
| $M_w$ | - | wind mixing parameter |

| | | |
|---|---|---|
| N | - | Ocean Station Vessel NOVEMBER |
| P | - | Ocean Station Vessel PAPA |
| $Q_b$ | - | effective back radiation |
| $Q_e$ | - | latent heat transfer |
| $Q_h$ | - | sensible heat transfer |
| $Q_l$ | - | net heat loss |
| $Q_n$ | - | neat heat transfer (cal-cm$^{-2}$) |
| $Q_r$ | - | reflected solar radiation (albedo) |
| $Q_s$ | - | solar insolation |
| $\rho_w$ | - | density of sea water |
| SH | - | swell height |
| SST | - | sea surface temperature |
| $\sigma$ | - | $4.88 \times 10^{-9}$ ly hr$^{-1}$ K$^{-4}$ |
| $\Delta T$ | - | temperature gradient($^{\circ}$F/100 feet) |
| $T_a$ | - | air temperature |
| $t_d$ | - | length of the day |
| $T_{max}$ | - | period of maximum energy |
| $T_w$ | - | water temperature |
| $T_{600}$ | - | sea water temperature at 600 feet |
| u | - | east-west component of surface current |
| V | - | wind speed |
| v | - | north-south component of surface current |
| WH | - | wave height |

## ACKNOWLEDGEMENTS

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# I. INTRODUCTION

With the increased emphasis on antisubmarine warfare and the development of various sonar range prediction models, it has become increasingly important that an accurate prediction of the ocean thermal structure be made available. Changes in ocean thermal structure, which occur mainly in the surface layer and the thermocline, are of major importance in determining variations in the vertical sound velocity profile. The sound velocity field determines the refraction pattern and the existence of surface ducts, sound channels and other sound transmission paths. Therefore, better data on the thermal structure will increase the reliability of predicting sonar performance.

The most important thermal structure parameter is the vertical extent of the surface duct, or the mixed layer depth. A surface duct will exist if: (1) the temperature increases with depth, or (2) an isothermal layer extends downward from the sea surface. In case (1), sound velocity increases with depth as temperature and pressure increase; in case (2), there is no temperature gradient and, in the absence of a salinity gradient, pressure causes sound velocity to increase with depth. The greater the depth of the mixed layer, the greater is the difference between the sound velocity at the surface and at depth. The number of sound rays which are trapped in the layer is therefore greater. Also, the deeper the layer, the fewer the surface

reflections which are required to reach a given range, with a resultant decrease in propagation losses. With increasing layer depth, the detection range increases for a target at its best depth to avoid detection. Thus it is evident that the mixed layer depth, to a great extent, determines the sonar ranges which will prevail. These variations in ray propagation with layer depth are illustrated in figure 1.

The mixed layer depth forecasting scheme presently in use at Fleet Numerical Weather Central (FNWC) is based primarily on climatology and analysis of previously reported conditions. Each day, the previous forecast field is adjusted towards climatology and then is modified by turbulent mixing due to wave action. This method of predicting mixed layer depth is rather elementary: the use of this model gives very little improvement over a prediction based on climatology or persistence (forecast conditions will be the same as present conditions). An exception occurs when wind mixing causes a significant change from climatology; under these conditions a fair correlation exists between the forecast and actual conditions. A more complete explanation of the method presently in use at FNWC is contained in Appendix A.

The purpose of this research is to produce a computerized mixed layer depth model for FNWC which will make a prediction of layer depth based on environmental conditions to replace the present one

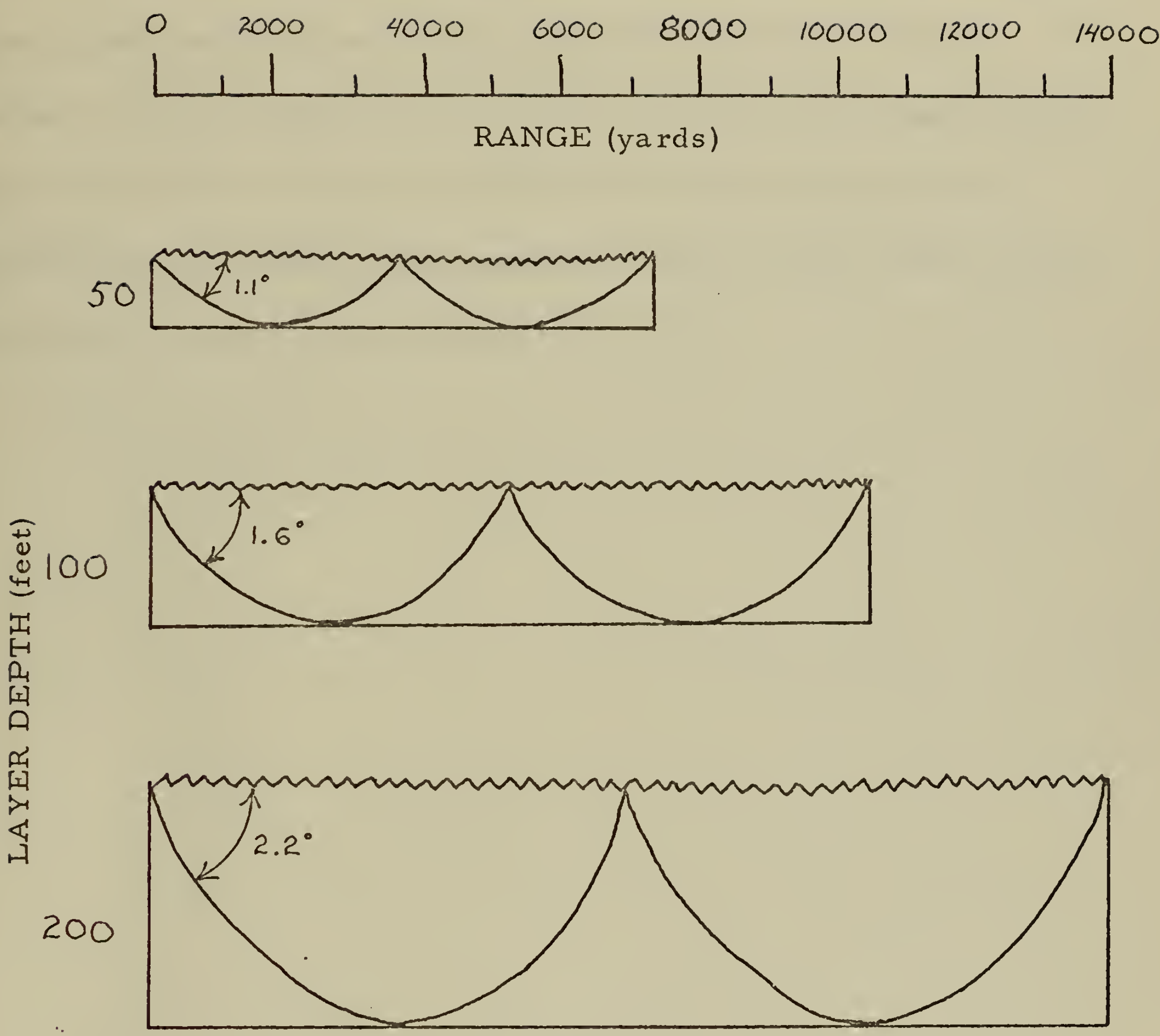



Figure 1. Variation of sound ray propagation with layer depth.

which is strongly dependent on climatology. The prediction method will be considered improved if the mixed layer depth produced proves to have a smaller percent error when compared to the verification layer depth than the layer depth produced by the FNWC analysis. A further check as to the accuracy of the prediction can be made by comparing the standard deviation of the forecast layer depth from the verification layer depth to the standard deviation of the FNWC method: 25 feet in the summer and 80 feet in the winter.

## II. PREVIOUS MIXED LAYER DEPTH STUDIES

Numerous studies relating to various aspects of the mixed layer depth have been conducted at the U. S. Naval Postgraduate School.

Clark [4] directed her attention to the upper layers of the atmosphere and such conditions that might possibly be associated with variations in the temperature structure of the ocean. She presented two hypotheses: (1) the upper mixed layer of the ocean and the layer of air in immediate contact with the ocean surface should be treated as a unit which is affected by meteorological parameters above this unit, (2) there exists in the upper atmosphere a 'mirror image' level where fluctuations in wind speed closely depict oscillations in the depth of the mixed layer. Clark reached the conclusion that a 'mirror image' level does exist in the atmosphere at an altitude of 6000 meters.

Geary [10] developed a model of mixing by wind generated wave motion and compared it to Laevastu's [18] and Neumann's [23] methods. He concluded that Laevastu's method gave the closest approximation to an upper limit on the observed mixing. He also stated the need for the development of a convective mixing model.

Edgren and MacPherson [8] used multiple regression analysis on various parameters (primarily meteorological) to examine the physical processes causing increases and fluctuations in the mixed layer depth.

It was determined that convection is the process which causes the seasonal increase of the layer depth during the cooling season and that short term fluctuations of the mixed layer are due primarily to internal waves.

Luskin [21] developed a simple model for mixed layer depth change by thermohaline convection and outlined a method for adapting the convection model for use as a forecast tool. He pointed out the need to develop a heat budget model for forecasting convective mixing.

Lambright [20] investigated the apparent random oscillation of the mixed layer depth and by the nature of its energy spectrum and its correlation with tidal activity, determined the source of some components of this oscillation.

Davis [5] investigated Bulgakov's model relating the depth of convective mixing to density and salinity changes in the upper layer of the ocean. He suggests the use of this model in taking into account the convective mixing due to increased density caused by mixing two or more layers of the ocean during the heating season.

Hancock [12] verified the Fleet Numerical Weather Central analyses and forecasts of mixed layer depth. The model verified in this study included convergence/divergence computations. The convective mixing influence was calculated from a change in sea surface temperature.

Ciboci [3] verified Mazeika's [22] method for Ocean Weather Station "P". It was found to be successful during the heating season

followed by a rapid decline as the cooling season began. He also determined that the forecasting curves developed by James [15] are easier to use than Mazeika's and provide a more accurate mixed layer depth forecast.

Kelley [16] studied a model based on Kitaigorodsky's application of similarity theory and modified by McDonnell to forecast mixed layer depth.

In this present work, an attempt is made to use various techniques previously developed to produce a forecasting method which takes into account heat budget calculations in computing the effect of convective mixing. The need for a model of this type has been stated many times and this study is a further step in the continuing quest to develop an accurate forecasting model for mixed layer depth.

# III. FACTORS AFFECTING MLD

The ocean may be considered to consist of three distinct layers: (1) the mixed upper layer, influenced by atmospheric conditions; (2) a zone of rapidly decreasing temperature called the thermocline also influenced by atmospheric conditions, and (3) a region of slower changes extending from the thermocline to the ocean bottom.

It is a feature of the mixed upper layer, specifically the depth at which this layer ends and the thermocline begins, that is of primary interest in this work. This depth is termed the mixed layer depth (or simply layer depth) and is defined as the depth of maximum temperature or the extent of the isothermal layer. The term isothermal is defined to include all positive gradients, and negative gradients up to and including $0.3^{\circ}F/100$ feet [15]. This definition is equivalent to the definition of sonic layer depth, the depth at which maximum sound velocity occurs in the layer above the thermocline [2]. Thus the two terms may be used interchangeably.

A number of methods are available for predicting the thermal structure of the oceans. These involve calculations of net heat exchange across the air-sea boundary, convective and wind mixing, continuity, and advective processes. Each procedure may be utilized separately, but the most accurate forecasts are generally made by considering the collective effects of all processes.

## A. NET HEAT EXCHANGE

The sea-surface temperature and the thermal structure immediately below the surface and its variations are greatly influenced by the heat exchange between the sea and the atmosphere. It is this energy exchange at the air-sea interface which forms the basis for the heat budget method of forecasting near-surface thermal conditions. The net heat gain or loss at the ocean's surface for the period of the forecast is computed from known or forecast values of sun's altitude, cloud cover, humidity, sea-surface temperature, wind speed, relative vapor pressure, and albedo. Of these parameters, only the sun's altitude is a truly-known quantity, while the others are forecast with varying degrees of accuracy. Heat budget computations are also of use in solving other problems, such as ice prediction, prediction of transient thermoclines and possibly the improvement of medium-range weather forecasts over the sea.

Once the total heat exchange has been calculated, the gain or loss of energy must be distributed throughout the water column. Qualitatively, heat gains often are associated with decreased layer depth while losses accompany layer depth increases.

## B. MIXING

The primary types of mixing considered in the formation of the mixed layer are: (1) instability (or convective) mixing produced by the sinking of dense water; (2) mixing as the result of convergence or

divergence causing the sinking or rising of water; and (3) mechanical (or forced) mixing, a turbulent transfer of momentum from one level to another by the combined action of wind waves and associated wind currents. All three types of mixing often occur simultaneously.

After calculating the magnitude of the heat gain or loss, convective mixing and mechanical mixing must be considered to determine heat distribution. For a net heat gain, implying a negative temperature gradient in the surface layer, wind mixing becomes the dominant factor in computing the mixed layer depth.

Although wind is the direct force involved in mechanical mixing, mixing in the water column is accomplished through the action of secondary phenomena- wind waves and pure wind currents. Swell can also contribute to mechanical mixing when combined with the effects of wind waves and currents. The mixing by waves is due primarily to the presence of waves of different period and height and to the turbulence caused by breaking. In the majority of cases, the seas are not fully developed, and wind speed alone cannot be used directly in the determination of mechanical mixing by the sea. In determining the thickness of a mixed layer created by wave action, the surface wave characteristics are first determined and then a depth is computed where particle motion and the resulting mixing are negligible.

The mixed layer depth due to mechanical mixing will depend on the wave model used. Since the singular wave forecasting model

(one which relates wave height to wind speed through a simple exponential relationship) is presently in use, only the simplest relationship between wave height and mixed layer depth is justified [19].

## C. CONVECTIVE MIXING

Although mechanical mixing is an important parameter in determining the mixed layer depth, it is not the only one. In fact, it may at times be entirely masked by other factors, such as convective mixing and convergence/divergence.

When the net heat exchange is from ocean to atmosphere (negative heat exchange), convective mixing is the dominant factor in determining the mixed layer depth. The upper layers of the ocean become unstable due to cooling and sink until they reach a stable level. This convection will result in isothermal mixing of the water to the level of stability.

After determining the effects of convective mixing, the wind-mixed layer depth is computed. If wind mixing is deeper than convection, the column is mixed isothermally to the wind-mixed depth. If the convective layer is deeper, no further modification is required.

## D. CONVERGENCE/DIVERGENCE

Pure wind currents may exert another influence on the layer in addition to the part they play in forced mixing. In an area in which there is a wind-created divergence of surface water (waters horizontally advected apart) the layer depth decreases since cooler water from intermediate depths must well upward to replace the divergent

surface waters. Similarly, a wind-produced convergence (waters flowing together) will cause an increase in the layer depth due to the sinking of the accumulated surface water.

## E. ADVECTION

Advective changes to the thermal structure are the most difficult to define with any degree of accuracy. The degree to which advection will affect the thermal structure is dependent upon the length of the forecast period, the local circulation, the horizontal temperature distribution, and the wind conditions. In areas where advection is determined to be of consequence, primary consideration is given to drift currents since their effects tend to be dominant. Permanent currents are assumed to be geostrophic (determined essentially by the temperature distribution if there is negligible salinity contribution) and thus produce no heat advection.

## F. INTERNAL WAVES

A primary factor which limits the predictability of the instantaneous mixed layer depth and verification of the forecast is the presence of internal waves on the interface between the mixed layer and the thermocline. Characteristically, these waves have large vertical displacements at the bottom of the mixed layer. While similar to surface waves, internal waves lack the turbulent interchange of momentum (a result of wave breaking) possessed by surface waves. Thus physical

mixing due to internal waves is not great unless these become breaking waves. Therefore, internal waves generally cause a periodic rise and fall of the mixed layer depth but do not seriously affect the average position of the bottom of the mixed layer. For this reason, as well as the lack of sufficient knowledge concerning the spectral distribution of internal waves, they were not considered in this study.

# IV. PROCEDURE

## A. DATA

In the development of this mixed layer depth forecast procedure, it was decided that available bathythermograph (BT) reports would be used to obtain the actual mixed layer depth (MLD) for use as a verification of the predicted value. For this reason, the investigation is concentrated in the vicinity of permanent ocean station vessels on the supposition that these locations would have the highest density of BT data available.

It was also desired to check the forecast model during different seasons; the study is confined to data from the months of January and September since these are quasi-stationary periods when mean physical parameters are relatively invariant.

First, a two degree latitude-longitude square around each of eight ocean station vessels was checked for the availability of BT data for ten-day periods in January 1972 and September 1971. Due to data limitations, the areas around Ocean Station Vessels (OSV) "E", "N", and "P" were selected as the locations for use in developing the procedure. The periods used were 10 to 20 September 1971 and 10 to 20 January 1972. Since these positions were not on a grid point for the standard FNWC analysis grid network, the data fields were interpolated to the OSV locations using linear interpolation between the four surrounding grid points.

For the periods selected, the FNWC fields of analyzed sea surface temperature, forecasted total heat exchange for the next 24 hours, u and v components of surface current, analyzed sea temperature at 600 feet, and forecasted wave and swell height were obtained. These fields were the input data to the forecast procedure. A brief description of each field is contained in Appendices B through F.

The order followed in producing the forecast can be seen in figure 2. The computer programs developed to produce the MLD forecast are included as Appendix H.

The first step in the process is to input an initial layer depth. This depth will be extracted from a BT taken 24 hours prior to the desired forecast time. The next step in the initialization phase is to input the data to be used in the forecast computation.

## B. FORCED MIXING (HEAT EXCHANGE POSITIVE)

The actual forecast procedure starts with the determination of whether the net heat exchange for the next 24 hours is positive or negative. If the net heat exchange is positive, the layer depth due to forced wind mixing is computed. Three methods of determining the depth of turbulent mixing are tested to determine which will give the best results.

The first method is an empirical formula based entirely on the significant wave height ($H_{1/3}$), suggested by Laevastu [19]:

$$MLD = 12.5\ H_{1/3} \tag{1}$$

The significant wave height used in this formula is actually the combined wave height (CH) due to both wave height (WH) and swell height (SH), calculated as follows:

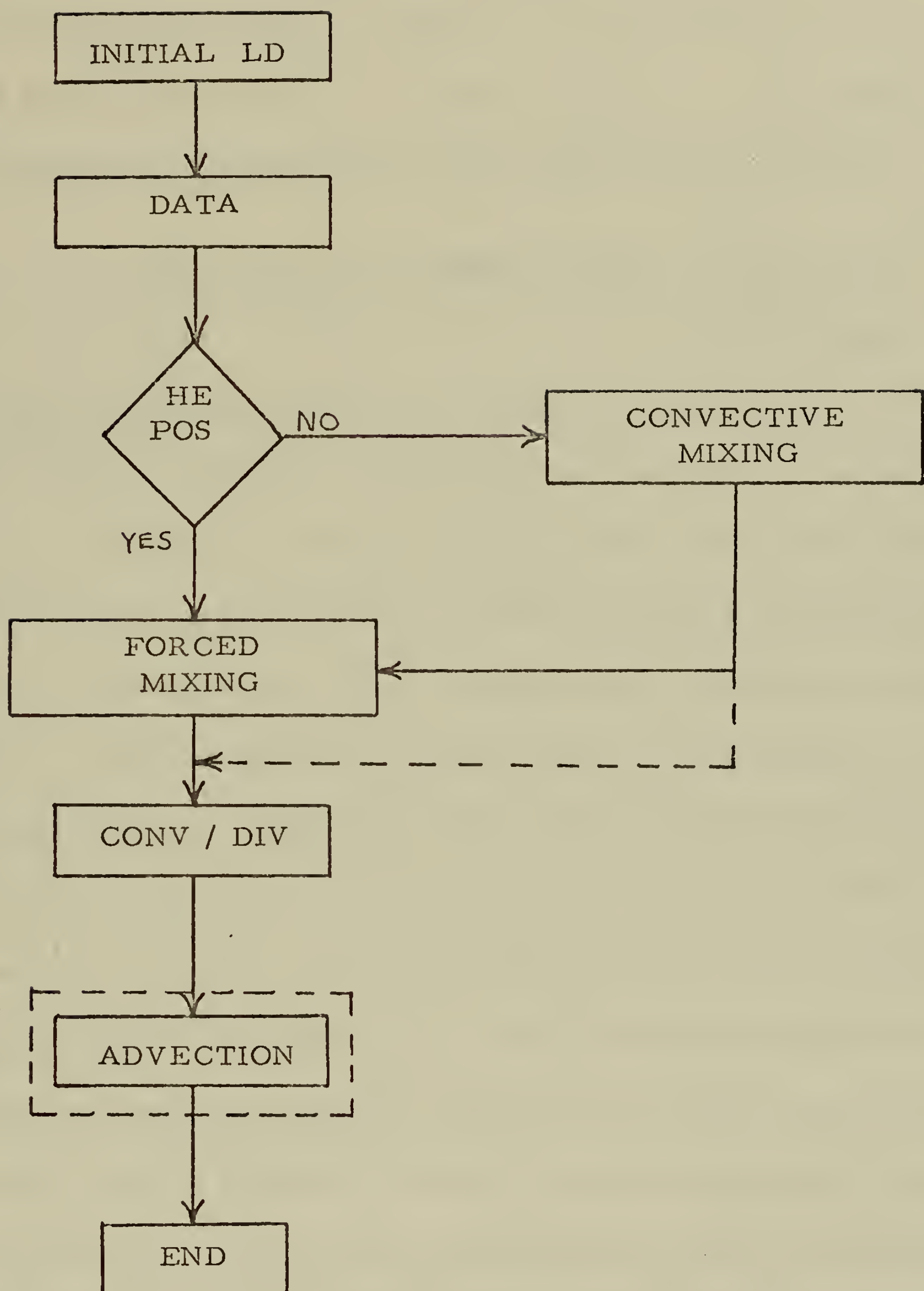



Figure 2. Mixed layer depth model flow diagram.

$$CH = \sqrt{WH^2 + SH^2} \tag{2}$$

The second method of forced mixing investigated is the one presently in use at FNWC. This also is based primarily on the combined wave height (CH), with a slight correction for the magnitude of the temperature gradient between the surface and 600 feet [9]:

$$\begin{aligned} MLD &= CH\,[\,11 - 0.1(SST - T_{600})\,] \qquad SST \geq T_{600} \\ MLD &= 11 \cdot CH \qquad\qquad\qquad\qquad\quad SST < T_{600} \end{aligned} \tag{3}$$

The final scheme tested is that suggested by James [15]. The first step in this method is to calculate the absorption of radiation by layers. Absorption coefficients by layers for various water types (clear oceanic, average oceanic, average coastal) are given by James. For the purposes of this study, average oceanic turbidity is assumed. This is a valid assumption since this model is not intended for use in coastal waters. For oceanic water, with a net heat exchange at the surface of 500 cal-cm$^{-2}$, the resulting temperature difference between clear oceanic and average oceanic water in the 0-20 foot layer is 0.08$^{\circ}$F. This difference is not of sufficient magnitude to justify the additional computer time required to make a determination of water type. In addition, absorption will be computed for only the 0-20 foot layer. This is done to decrease the number of computations needed and is considered valid, since an input at the surface of 500 cal-cm$^{-2}$ is required to produce a change in temperature of 0.1$^{\circ}$F in the 20-40 foot layer while this same energy input at the

surface would cause a change of 1.3 $^{\circ}$F in the 0-20 foot layer. It is the gradient in this shallow layer which must be overcome by mechanical mixing. The average change in temperature in the layer due to the surface heating is calculated, and is then added to the original temperature at the ten-foot level. A linear gradient is assumed through this point between the surface and the original trace at 20 feet.

The next step is to compute a mixing parameter ($M_w$) which is a function of significant wave height ($H_{1/3}$) and the period of maximum energy ($T_{max}$) [15]:

$$M_w = T_{max} H_{1/3} \quad . \tag{4}$$

The $T_{max}$ in this case is the period of maximum energy which would be present for a fully developed sea having the given significant wave height. The combined wave height (equation 2) is again used in this case as the significant wave height. Once this mixing parameter has been computed, it is used with the temperature gradient of the 0-20 foot layer to compute the layer depth [15]:

$$LD = \frac{K_1}{\Delta T} \left( 1 - e^{-K_2 \, \Delta T M_w} \right) \tag{5}$$

where $K_1$ and $K_2$ are constants.

## C. CONVECTIVE MIXING

For the situation of a net heat loss to the atmosphere, layer depth change due to convective mixing must be calculated. This is accomplished using a method set forth by James [15]. The first step is to calculate the convective mixing parameter, $M_c$:

$$M_c = \frac{2\,Q_1}{C_p\,\rho_w\,\Delta T} \tag{6}$$

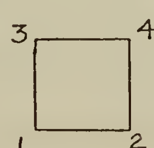
where $Q_1$ is the net heat loss in gram cal.-cm$^{-2}$, $C_p$ is the specific heat of sea water and is assumed to be constant at 0.935 cal/gm/$^{\circ}$C, $\rho_w$ is the density of sea water and is assumed to be constant at 1.024 gm/cm$^3$, and $\Delta T$ is the average temperature gradient from the bottom of the initial layer to 600 feet in $^{\circ}$F/100 feet. $M_c$ is then combined with the initial layer depth ($h_o$) to give the mixed layer depth due to convection as follows:

$$LD = \sqrt{(h_o)^2 + (M_c)^2}\ . \tag{7}$$

The next step is to calculate the forced mixed layer depth using one of the methods described in the previous section. The mechanical and convective mixed layer depths are then compared and the deeper one is taken to be the actual layer depth. In various references, it has been suggested that when convective mixing is present, mechanical mixing can be ignored. This suggestion is also tested.

## D. CONVERGENCE/DIVERGENCE

The effect of convergence or divergence on the layer depth is then determined. This is accomplished through the use of the u and v components of surface current, which are combined to give a change in layer depth due to convergence or divergence as follows [12]:



$$LD = 0.864\ (U_1+U_3-U_2-U_4+V_3+V_4-V_1-V_2)\ \ LD/4L$$

where 0.864 is a dimensional constant to change the variation in the layer depth from the metric system to feet, and L is the distance between grid points. The decision to work in feet rather than meters was made in order to decrease the number of calculations (wave heights, swell heights, layer depths and temperature gradients are all in feet). This value for the change in layer depth is then added to the layer depth previously calculated and the result is the predicted mixed layer depth.

## E. ADVECTION

The advection of heat and the change in the thermal structure due to this advection is then computed.

For the areas under investigation, it was noted that due to the slight temperature gradient between grid points (maximum of 0.01 $^\circ$F per nautical mile) and the small currents (maximum transport on the order of 50 nautical miles per day) the temperature change due to advection would be no more than 0.2 $^\circ$F/day at any time.

Due to the difficulty in describing advection accurately and the variable contribution it makes in the areas under investigation, the decision was made to disregard advection in this study.

## F. FITTING THE FORECAST TO DATA

At this point in an operational procedure, the latest BT reports are read into the program and the forecast field is adjusted

accordingly with respect to the reported layer depth and the age of the BT report. In this study, this step was omitted since the actual BT reports were the basis for determining the accuracy of the forecast.

# V. RESULTS

## A. COMPARISON OF MECHANICAL MIXING FORMULAS

In order to determine the mechanical mixing method to be used in the procedure for the prediction of mixed layer depth, calculations of forced mixing were made using each of the three proposed relationships. In relat  n to the complete forecasting model (figure 2), the calculations in this section refer only to the forced mixing step. The heat exchange is given as positive. The data input are combined wave height and the temperature gradient between the surface and 600 feet. All remaining steps in the model are ignored. The computations were made for five specified periods when mechanical mixing was the determining factor in the forecast layer depth. This is the case when the heat exchange is positive. The combined wave height (CH) was also a factor in selecting the period to be investigated; computations were desired for a range of wave heights. The layer depth from each relationship and the observed layer depth are compared in Table I. The percent error from the actual conditions (in parentheses) and the combined wave height for the forecast period are also shown.

For reference, the equations of the three relationships are as follows:

1. Laevastu

$$LD = 12.5\ CH \qquad (9)$$

2. FNWC

$$LD = CH\,[11 - 0.1(SST - T_{600})] \qquad SST \geq T_{600} \qquad (3)$$

$$LD = 11 \cdot CH \qquad SST < T_{600}$$

3. James

$$LD = \frac{K_1}{\Delta T}\,(1 - e^{-K_2 \quad \Delta TM_w}) \qquad (5)$$

A comparison of the Laevastu formula to the FNWC one shows that the FNWC will always produce a shallower forecast. The FNWC constant (11) is 12% smaller than the Laevastu constant (12.5) thus producing a forecast layer depth due to mechanical mixing which, in the absence of a temperature gradient between the surface and 600 feet, will be 12% less than the forecast produced by the Laevastu formula; as the temperature gradient between the surface and 600 feet increases in magnitude, the differences between the layer depths forecast by the two methods increases.

In comparing the Laevastu results to those of James it was noted that the percent difference between the two layer depths varied with the wave height. With wave heights of the order of five feet, the difference between the two models was less than 10% (absolute differences in the range 1-5 feet). As the wave height increased to 10-20 feet, the James model produced layer depths approximately 18% greater. With a large wave height (26.6 feet) the Laevastu model produced a layer over 50% deeper than the James model, and 18% shallower than the observed layer depth.

TABLE I. Comparison of layer depths in feet produced by various mechanical mixing formulas. Numbers in parentheses are percent error from observed conditions. Combined wave height (CH) in feet and net heat exchange ($Q_n$) in cal/cm$^2$ are indicated for each case. $Q_n$ is positive in all cases.

| | CH | $Q_n$ | LAEVASTU | FNWC | JAMES | OBSERVED |
|---|---|---|---|---|---|---|
| 1. | 4.3 | 281 | 54 (51.9) | 41 (62.7) | 50 (54.5) | 110 |
| 2. | 4.7 | 67 | 59 ( 1.7) | 45 (25.0) | 60 ( 0 ) | 60 |
| 3. | 10.4 | 25 | 131 (69.5) | 112 (74.0) | 160 (62.8) | 430 |
| 4. | 18.5 | 257 | 231 (43.5) | 200 (51.1) | 270 (34.0) | 409 |
| 5. | 26.6 | 308 | 332 (18.2) | 287 (29.3) | 160 (60.6) | 406 |

One aspect of the three mechanical mixing relationships which should be noted is that as the net heat gain at the ocean's surface becomes larger, the FNWC and James models produce shallower layer depths due to the influence of the increased thermal gradient in the upper layer. The Laevastu formula contains no consideration of heat gain.

Only in case 2 (Table I) was an accurate prediction of layer depth under the influence of mechanical mixing produced (by the Laevastu and James relations). Cases 1 and 2 occurred in September during a period of decreasing surface heating and low wave height when the layer depths were relatively shallow (60 to 160 feet). In these cases, the wind mixing was not sufficient to keep the surface layer mixed below 60 feet and after two days of surface heating, a shallow transient layer was formed (the layer at 60 feet was destroyed the following day by convective mixing).

The Laevastu relation exhibited fair results (18% error) in case 5. Cases 3 through 5 occurred in January during a period of increasing surface heating and large combined wave height when the layer depth was fairly deep (400 feet). For these cases, although the surface heating was large, the mechanical mixing was of such magnitude that a shallow surface layer could not form.

It appears that there is some relationship between mechanical mixing, heat exchange, and the initial layer depth which determines whether a layer will be formed which conforms to the mechanical

mixing term or if the mechanical mixing will act to maintain the original deep layer by preventing the formation of a shallow layer. When the conditions are such that the mechanical mixing acts to eliminate the shallow layer, none of the mechanical mixing methods investigated here produce accurate forecasts for the deeper layer.

After a consideration of the preceding factors, it was decided to use the Laevastu formula for predicting mechanical mixed layer depth in the model tested in this study. The Laevastu formula was chosen over the FNWC on the basis of the smaller error between the forecast and observed layer depth. The James formula was eliminated primarily due to the difficulty in computerizing it (computations in Table I were produced manually). This was not the only consideration however, as the accuracy of the two methods (Laevastu and James) was also compared. At wave heights up to 20 feet, there was little difference in the two while in the fifth case (wave height of 26.6 feet) the Laevastu result was much better (18% vs. 60%).

The difficulty in computerizing the James model arises from the fact that the constants ($K_1$ and $K_2$) in equation 5 vary with the temperature gradient. One possible solution for this is to use a nomogram provided by James [15] to produce a grid of layer depths with the wind mixing parameter as one ordinate and the temperature gradient as the other. This could be done but the computer time required for the grid search in each case would be prohibitive.

## B. DAILY FORECASTS

Using the various procedures outlined in Section IV, mixed layer depth forecasts were produced for selected 24-hour periods. In making the forecasts in this and the following section, each applicable step of the model (figure 2) was considered (the path taken depending on whether the heat exchange was positive or negative). For the forecasts in this section, the initial layer depth was determined from the BT report taken 24 hours prior to the forecast time. The criterion for the selection of a forecast period was the availability of BT data for use as the initial layer depth and as a verification of the accuracy of the forecast. The forecasts are shown in the computer output section (Appendix I).

The purpose of this phase was to check the accuracy of the forecast over a 24-hour period using an accurate layer depth as an input. The observed layer depth, forecast layer depth and the FNWC analysis of the layer depth at the forecast time for each forecast are shown in Tables II thru V. The percent error between the forecast and observed layer depth and the FNWC analysis and the observed layer depth were calculated for each case and are displayed as the value in parentheses in each table. The last line of each table shows the average standard deviation of the forecast layer depth from the observed layer depth and the FNWC analyzed layer depth from the observed layer depth.

1. January, Station "N"

The results for this forecast period are contained in Table II. These forecasts were made for a period of substantial negative heat exchange (-400 cal/cm$^2$ to -200 cal/cm$^2$) with combined wave heights of 6-11 feet. The procedure exhibited improved accuracy in two of the four cases. For the periods when the FNWC analysis was more accurate, the improvement was only about 2% in each case. The maximum error in the procedure was 7.9% while the analysis had two values with an error greater than 8%. With respect to predicting the average conditions for the period, the procedure exhibited an error of 3.6% with an average standard deviation of 29 feet as compared to -7.5% and 53 feet for the FNWC analysis.

The FNWC analysis was less than the observed conditions in every case while the procedure forecast was higher in all but one case.

2. January, Station "P"

Results are shown in Table III. The first two forecasts were for periods of small heat exchange (-90 cal/cm$^2$ and 25 cal/cm$^2$ respectively) while the remaining four were for a period of substantial negative heat exchange (-250 cal/cm$^2$). The combined wave height for the period was 10-13 feet. For this period, the FNWC analysis proved to be more accurate in four of the six cases and close to the model (less than 2% difference in percent error) in the remaining

TABLE II. Comparison of observed MLD, forecast MLD, and FNWC MLD analysis (in feet) for Station "N", January (numbers in parentheses are percent error).

| TIME | DATE | OBSERVED | FORECAST | FNWC |
|---|---|---|---|---|
| 00 | 12 | 530 | 552( 4.2) | 483(- 8.9) |
| 12 | 12 | 570 | 561(- 1.9) | 499(-12.5) |
| 00 | 13 | 510 | 531( 4.1) | 502(- 1.6) |
| 12 | 13 | 530 | 572( 7.9) | 497(- 6.2) |
| AVERAGE | | 535 | 554( 3.6) | 495(- 7.5) |
| STD. DEV | | | 29 | 53 |

TABLE III. Comparison of observed MLD, forecast MLD, and FNWC MLD analysis (in feet) for Station "P", January (numbers in parentheses are percent error).

| TIME | DATE | OBSERVED | FORECAST | FNWC |
|---|---|---|---|---|
| 00 | 13 | 360 | 400( 11.1) | 391( 8.6) |
| *12 | 13 | 430 | 130( 69.8) | 404(- 6.0) |
| 00 | 19 | 390 | 440( 12.8) | 389(- 0.2) |
| 12 | 19 | 410 | 386(- 5.9) | 404(- 1.5) |
| 00 | 20 | 380 | 403( 6.1) | 405( 6.6) |
| 12 | 20 | 460 | 420(- 8.7) | 412(-10.4) |
| AVERAGE | | 405 | 363(-10.4) | 400(- 1.2) |
| STD. DEV. | | | 139 | 30 |

* indicates positive heat exchange

two cases. The maximum error for the FNWC analysis was 10.4% while that for the procedure was -69.8%. The procedure failed to produce a forecast which was within 5% of the observed layer depth for any case.

In forecasting the average conditions, the procedure had an error of -10.4% with an average standard deviation of 139 feet while the FNWC analysis had an error of only -1.2% and an average standard deviation of 30 feet.

3. <u>September, Station "N"</u>

Results are shown in Table IV. The net heat exchange for the first two forecasts is positive; the heat exchange for the remainder of the period is negative, increasing from -83 cal/cm$^2$ to -200 cal/cm$^2$ during the period. The combined wave height throughout the forecast period is 2-6 feet. In comparing the two schemes, the results of 00Z on the 19th are discounted since, although the FNWC analysis had a smaller error, neither was within 500% of the observed layer depth (this value was included in the calculation of the average layer depth and the average standard deviation). Of the remaining 10 forecasts, the FNWC analysis proved to be more accurate in six cases; however, the best result obtained was an error of 7.9%.

The procedure showed an error of 15% in forecasting average layer depth with an average standard deviation of 85 feet. The FNWC analysis had a 3.8% error in predicting average conditions with an average standard deviation of 52 feet.

TABLE IV. Comparison of observed MLD, forecast MLD, and FNWC MLD analysis (in feet) for Station "N", September (numbers in parentheses are percent error).

| TIME | DATE | OBSERVED | FORECAST | FNWC |
|---|---|---|---|---|
| *00 | 13 | 110 | 53(- 51.8) | 132( 20.0) |
| *12 | 13 | 60 | 59(- 1.7) | 143(138.0) |
| 00 | 14 | 180 | 110(- 38.9) | 141(-21.7) |
| 12 | 14 | 160 | 60(- 62.5) | 141( 9.2) |
| 00 | 16 | 150 | 151( 0.7) | 138(- 8.0) |
| 12 | 16 | 180 | 132(- 26.7) | 138(-32.3) |
| 00 | 19 | 20 | 191( 855.0) | 135(575.0) |
| 12 | 19 | 140 | 160( 14.3) | 129(- 7.9) |
| 00 | 20 | 170 | 28( 83.5) | 137(-25.3) |
| 12 | 20 | 170 | 141( 17.1) | 137(-19.4) |
| AVERAGE | | 133 | 113(- 15.0) | 138( 3.8) |
| STD. DEV. | | | 85 | 52 |

* indicates positive heat exchange

4. January, Station "E"

Results are presented in Table V. The net heat exchange for the first two forecasts is approximately -400 cal/cm$^2$; for the remaining forecasts the heat exchange is approximately -70 cal/cm$^2$ with the exception of 00Z on the 16th when there was a positive heat exchange of 9 cal/cm$^2$. The combined wave height during the period is 3-7 feet. For the first forecast layer depth, both methods show a large error; in the remaining five cases, the procedure presented in this study is more accurate four times.

In predicting average conditions, all forecasts were included (the forecast for 00Z on the 12th was not considered in computing the average standard deviation). The procedure exhibited an error of 36.7% with an average standard deviation of 80 feet while the FNWC analysis had an error of 6% and an average standard deviation of 240 feet.

5. Summary

Large deviations of the results from observed conditions occur primarily when the net heat exchange at the ocean surface becomes positive for a short period of time. In this case, the layer depth forecast by the model is determined entirely by mechanical mixing. When this happens, the result is the prediction of the formation of a shallow layer (as the 12Z forecast on the 13th in Table III and the 00Z forecast on the 20th in Table IV show) but this may not occur. To correct this problem, some method must be devised to

TABLE V. Comparison of observed MLD, forecast MLD, and FNWC MLD analysis (in feet) for Station "E", January (numbers in parentheses are percent error).

| TIME | DATE | OBSERVED | FORECAST | FNWC |
|---|---|---|---|---|
| 00 | 12 | 110 | 910(727.0) | 422(284.0) |
| 12 | 12 | 580 | 661( 14.0) | 434(-25.2) |
| 00 | 15 | 620 | 770( 24.2) | 531(-14.4) |
| 12 | 15 | 650 | 679( 4.5) | 544(-16.3) |
| *00 | 16 | 100 | 47( 53.0) | 493(393.0) |
| 12 | 16 | 670 | 666(- 0.5) | 464(-30.7) |
| AVERAGE | | 455 | 622( 36.7) | 481( 5.7) |
| STD. DEV. | | | 80 | 240 |

* indicates positive heat exchange

determine whether this predicted shallow layer will actually form or whether the deeper layer will persist. This could perhaps be related to some value of wind mixing which will cause turbulence to such an extent that a shallow layer cannot form. Another method would be to set a limit (either absolute or a percentage) on the decrease in layer depth which would be permitted to occur. When this limit was exceeded, the forecast mixed layer depth would be forecast by persistence (the forecast layer is the same as the present layer depth).

Large errors between the FNWC analysis and the observed conditions occurred due to the deviation of the observed conditions from climatology. The variability of the climatological data is presently being evaluated by FNWC and others.

Although internal waves were disregarded in this study, it is of value to note their possible effect on the accuracy of the forecast. Assuming an average amplitude of 40 feet for the internal waves affecting these forecasts, the forecasts can be considered to be 100% correct if they are within $\pm 40$ feet of the average observed layer depth. Applying this assumed internal wave amplitude to the forecasts yields an accuracy of 90% in the first two cases (Tables II and III). For the other two periods, the improvement is negligible, indicating that perhaps other factors are present or that larger internal waves are present.

Examination of the average standard deviations indicates that although the average standard deviation may be large, both the

procedure and the FNWC analysis should be able to predict the average conditions with some degree of accuracy.

## C. CONTINUOUS FORECASTS

The purpose of this phase was to see if the procedure could take an actual layer depth (from the BT report taken 24 hours prior to the forecast time) as a starting point and make successive forecasts for a period of time using the forecast mixed layer depth as the starting point for each succeeding prediction. It was hoped that after running the model for a period of time in this way, the difference between the resulting forecast layer depth and the observed condition would be minimal. The forecasts are shown in the computer output section (Appendix I).

The criterion used in selecting the periods used was the availability of observed layer depths throughout the period for use in making a comparison of the accuracy of each forecast. The forecast MLD, observed MLD, and the percent error between the two are shown in Tables VII thru X.

### 1. <u>January, Station "N" (00Z forecasts)</u>

Results are shown in Table VI. The procedure worked well (maximum error of 8.4%) for the first three days. On the fourth day, there was a positive heat exchange, thus causing convective mixing to cease and the forecast layer depth was determined by mechanical mixing. Since mechanical mixing was small on this day, the layer

TABLE VI. Comparison of the forecast MLD to the observed MLD (in feet) and the percent error between the two for Station "N", January (00Z forecasts).

| DATE | FORECAST | OBSERVED | % ERROR |
|---|---|---|---|
| 12 | 552 | 530 | 4.2 |
| 13 | 553 | 510 | 8.4 |
| 14 | 554 | 520 | 6.5 |
| *15 | 43 | 540 | -92.0 |
| 16 | 82 | 440 | -81.4 |
| 17 | 115 | 540 | -78.7 |
| *18 | 46 | 520 | -91.1 |
| 19 | 77 | 500 | -84.6 |
| 20 | 87 | 590 | -85.2 |
| AVERAGE | 234 | 521 | -55.1 |

* indicates positive heat exchange

depth was forecasted to decrease drastically (from 520 feet to 43 feet) while actually it increased by 20 feet. Since this layer depth (43 feet) was used as the initial layer depth for the next forecast, the large error (80%) was propagated throughout the remainder of the period. Positive heat exchange again occurred on the 18th which caused the layer again to decrease; this stopped the growth which was occurring due to convective mixing.

Calculations were made to determine the effect on the accuracy of the forecast if for the forecast on the 15th, persistence of the layer depth on the 14th (554 feet) were forecast rather than the mechanical mixing layer depth (42 feet). The forecast procedure is then followed as before until the 18th when again the layer depth for the previous day is forecast to persist. The result of this modified forecast is that the procedure predicts the average layer depth with an error of 6.3% and an average standard deviation of 53 feet. These values compare favorably with the values computed for the three days on which good forecasts were obtained originally (6.3% and 41 feet).

2. <u>January, Station "P" (00Z forecasts)</u>

Results are shown in Table VII. The results for this period were very good although there were three days during the period for which no BT observations were available for comparison.

This period was a time of strong wind mixing (18 to 25 foot combined wave height) in addition to being an interval of substantial convective mixing. The large mechanical mixing on the 14th and 15th

TABLE VII. Comparison of forecast MLD to the observed MLD (in feet) and the percent error between the two for Station "P", January (00Z forecasts).

| DATE | FORECAST | OBSERVED | % ERROR |
|---|---|---|---|
| 13 | 370 | 390 | - 5.1 |
| *14 | 233 | --- | ----- |
| *15 | 336 | --- | ----- |
| 16 | 336 | 330 | 1.8 |
| 17 | 340 | --- | ----- |
| 18 | 348 | 430 | -19.1 |
| 19 | 357 | 390 | - 8.5 |
| 20 | 369 | 380 | - 2.9 |
| AVERAGE | 336 | 384 | -12.5 |

* indicates positive heat exchange

prevented a drastic decrease in the forecasted layer depth thus averting the large errors which occurred at Station "N" as previously noted.

A stated desire of this phase was to have a minimal difference between the final forecast layer depth and the observed condition. This was accomplished for this forecast period with a difference of only 11 feet (-2.9%) on the last day.

The average standard deviation for this period was 48 feet with an error of -12.5% in forecasting the average layer depth.

3. <u>September, Station "N" (00Z forecasts)</u>

Results are shown in Table VIII. The results were unsatisfactory with errors ranging from 50% to 85% between the forecasted and observed layer depths. This was due again to light mechanical mixing which allowed the initial layer depth on the first day to decrease rapidly (140 feet to 29 feet) while the layer actually deepened 20 feet. This period was dominated by positive heat exchange (3 of 4 days) with convective mixing on the last day being ineffective in producing an accurate forecast due to the shallow initial layer depth.

Again, the effect of forecasting persistence for the first three days with the calculation of the layer depth on the fourth day based on the persisted layer depth was investigated. The errors in this case between the forecast and observed layer depths were in the range, 13% to 21%. In predicting the average layer depth, this modified model had an error of 2% and an average standard deviation of 33 feet.

TABLE VIII. Comparison of the forecast MLD to the observed MLD (in feet) and the percent error between the two for Station "N", September (00Z forecasts).

| DATE | FORECAST | OBSERVED | % ERROR |
|---|---|---|---|
| *11 | 29 | 160 | -81.9 |
| *12 | 19 | 120 | -84.2 |
| *13 | 53 | 110 | -51.8 |
| 14 | 56 | 180 | -68.9 |
| AVERAGE | 39 | 143 | -72.7 |

* indicates positive heat exchange

4. <u>September, Station "N" (12Z forecasts)</u>

Results are shown in Table IX. This period also produced bad results with the exception of the forecast for the 13th which had a -1.7% error. Errors on the remaining days ranged from 45% to 70%.

The first three days were controlled by the positive heat exchange and thus, with no convective mixing occurring, the layer depth was determined by mechanical mixing. Since the mixing was small (3 to 5 foot combined wave height) the surface heating produced a shallow transient layer of 60 feet after three days and the only good forecast. When convective mixing occurred the following day, the transient layer was destroyed but the convective mixed layer depth model in use is such that a drastic increase in layer depth cannot be forecasted. Therefore, although convective mixing was the driving force during the final three days, the forecasted layer depth continued to lag behind observed conditions.

5. <u>Summary</u>

Large deviations of the model from observed conditions occurred mainly when an amount of heat was added and mechanical mixing followed for one or more days causing the formation of a shallow mixed layer (as shown by figures 3 through 5 of Appendix G); the convective mixing model was unable to quickly eliminate the shallow thermocline upon the return to a negative heat exchange.

The one series of good forecasts occurred for a period when both convective and mechanical mixing were substantial. The large

TABLE IX. Comparison of the forecast MLD to the observed MLD (in feet) and the percent error between the two for Station "N", September (12Z forecasts).

| DATE | FORECAST | OBSERVED | % ERROR |
|---|---|---|---|
| *11 | 39 | 130 | -70.0 |
| *12 | 49 | 160 | -69.3 |
| *13 | 59 | 60 | - 1.7 |
| 14 | 59 | 160 | -63.1 |
| 15 | 72 | 130 | -44.6 |
| 16 | 74 | 180 | -58.9 |
| AVERAGE | 59 | 137 | -56.9 |

* indicates positive heat exchange

mechanical mixing prevented the formation of a shallow layer until convective mixing again became dominant.

As in the daily forecasts discussed in the previous section, the need is evident for some method of predicting the formation of a shallow layer during periods when mechanical mixing is dominant. Possible methods of accomplishing this are discussed in the summary of the previous section.

## D. CONVERGENCE/DIVERGENCE CORRECTIONS

To determine the effectiveness of the convergence/divergence corrections, the daily forecasts were studied to determine whether or not the correction improved the accuracy of the forecasted layer depth. The daily forecasts were selected in order to avoid errors caused by poor input data.

In determining whether the convergence/divergence corrections were of any advantage, any correction less than one foot was determined to have produced no effect. Also, no determination of the effect of the correction on the accuracy of the forecast was made for those cases in which there was a large discrepancy between the forecast and observed layer depths.

The first forecasts studied were for Station "N" in September and January. The maximum correction for this set of data was three feet. Of 15 forecasts which were considered to exhibit satisfactory accuracy,

convergence/divergence had no effect in nine cases. In the remaining six cases, the correction improved the accuracy half the time.

The second forecast period studied was Station "P" in January. Four of the six corrections for this period were in the range, 9 to 11 feet. Of the six forecasts, one correction produced no effect while three decreased the accuracy and two improved it.

The final period investigated was January at Station "E". Four of the six corrections in this case were in the range, 11 to 19 feet. Applying the correction increased the accuracy in one case while it was decreased in two others. There were three forecasts in which the correction had no effect.

It is evident that although there are locations where convergence/divergence has very little effect (Station "N") there are areas where it must be taken into account (Stations "P" and "E"). It was also noted that of 14 occasions when the convergence/divergence correction had some effect, it improved the accuracy of the forecast only in six cases.

# VI. CONCLUSIONS AND RECOMMENDATIONS

The results of this study indicate that the model which was developed will produce a slightly more accurate forecast than the FNWC formula when there is substantial convective action and the conditions vary from climatological conditions (Table II). Under these conditions the model had a maximum error of 7.9% and a standard deviation of 29 feet. This is compared to a maximum error of 12.5% and a standard deviation of 53 feet for the FNWC formula.

The greatest source of error in the model developed in this study is when convective mixing ceases for a short time. When this happens, the forecast layer depth is based on the layer depth due to mechanical mixing and this at times forecasts a decrease in the layer depth of up to 400 feet. This is a serious flaw in the model and work needs to be done in this area. What is actually happening, is the formation of a new shallow layer (rather than the deep layer being destroyed) for a short period of time with a return to a deep layer as soon as either convective or mechanical mixing becomes sufficiently strong to destroy this transient shallow layer. Work must be done in this area to determine under exactly what conditions a shallow layer will form or be prevented from forming. Two methods which might be used to improve the accuracy of the forecast until such time as improved methods are available are as follows:

1. Make a persistence forecast in the event of a forecast of a drastic change in layer depth.
2. Allow the layer depth to decrease only a certain percent of the difference between the previous layer depth and the forecast layer depth.

In comparing the mechanical mixing relationships, the Laevastu method (used in this study) was more accurate than the FNWC method. In the one good forecast of mechanical mixing investigated, the FNWC relation had an error of 25% (compared to 1.7% for the Laevastu relation) and the next best result obtained was an error of 29.3% (compared to 18.2% for Laevastu's method). An area of further study concerns this Laevastu method. It is possible that the constant should be changed, perhaps to a second order term in combined wave height. This is suggested by the fact that as the combined wave height increased (from 5 to 27 feet) the error between the forecast and observed conditions decreased (from 70% to 18%).

It appears that convergence/divergence is a factor, particularly for Stations "P" and "E". However, the method used in this study to compute the correction for convergence/divergence produced a correction which improved the accuracy of the forecast less than half the time. Since FNWC is now in the process of improving their surface current analysis model, this factor should be investigated at a future time.

The basic conclusion reached from this study is that the James method for convective mixing can be computerized and forecasts can be produced which take the heat budget into consideration. The accuracy of this model is restricted by the accuracy of the input data, particularly that of the initial layer depth. Given an accurate layer depth, this model has demonstrated the ability to make a continuing forecast using forecast layer depths as input data (during periods of large negative heat exchange) until such a time as a new BT report is available (Table VIII).

## APPENDIX A

## FNWC POTENTIAL LAYER DEPTH METHOD

The first step in the FNWC layer depth forecast method is the construction of the layer depth analysis.

The initial step in the analysis is to adjust the 12-hour-old potential layer depth field toward the interpolated climatological field of the analysis time. This interpolated field is a linear interpolation over two months; the present and preceding month if the day is less than 15, or the present and following month if the day is more than 15. If the analysis is for the 15th, only the climatology of the present m month is used. This adjusted climatological field is the first guess field.

Next, the mixed layer depth possible due to wave mixing alone is computed from the combined wave height analysis as follows:

$$\begin{aligned} MLD &= CH[11-0.1(SST-T_{600})] & \qquad SST &\geq T_{600} \\ &= 11\ CH , & \qquad SST &< T_{600} \end{aligned}$$

The effect of the term, $0.1(SST-T_{600})$, is to reduce the depth of mixing when a strong thermocline gradient exists.

The mixed layer depth field due to wave action is then smoothed with a special smoothing function designed to decrease the highest values in the field without increasing the values at any point.

Next, the MLD field due to wave mixing is compared to the initial-guess field produced from climatology and the deeper of the two is chosen as the second-guess MLD field.

The final step in the analysis phase is to adjust this second guess field to BT reports taken within the past 72 hours. The reports are weighted, based on the age of the observations at analysis time with the latest reports receiving the greatest weight. One final control placed on the analysis field is to force the layer depth to be less than or equal to 900 feet at all grid points. The result is the FNWC potential mixed layer depth analysis field.

The forecast layer depth field is produced in the same manner as the analyzed field. The analyzed field is adjusted toward the climatology of the forecast time using the method described for producing the analysis. The mechanical mixing is then computed using the 24-hour forecast combined wave field. The same steps of comparison and smoothing are taken between the wind mixed field and the climatological field. The result is the forecast potential mixed layer depth field.

The one difference in procedure between the analysis and forecast phase is that the forecast field is not adjusted to BT reports.

A severe constraint on this method is the lack of data which results in relying essentially on climatology in areas of sparse data. An additional problem area is that this forecast scheme is also subject to errors in the wave height forecast.

# APPENDIX B

## FNWC SEA SURFACE TEMPERATURE ANALYSIS

The sea surface temperature analysis is accomplished through a scheme called Fields By Information Blending (FIB). The analysis is done on a 125x125 grid with an output on a 63x63 grid.

Inputs to the analysis are sea surface temperature reports within six hours of the analysis time and surface temperatures from BT reports received in the past 12 hours. When it becomes readily available, satellite data also will be incorporated in the model.

The first step in the analysis is to compute the current climatology. This climatology is then assigned a weight based on the gradient of temperature between grid points (highest gradients are given the lowest weights). Next, the first guess field is produced by blending the previous analysis and the current climatology.

The next step is to read in and screen the sea surface temperature reports. A difference field is computed by subtracting the first guess field from the field produced from reports. Each report is assigned a weight based on its age.

The final sea surface temperature analysis is produced by blending this difference field with the guess field using the assigned weights.

The basic drawback to this procedure is the fact that 1100 to 1200 reports are input to produce an analysis over 3969 grid points. Obviously, some accuracy is lost through smoothing. The procedure should become better once satellite data are routinely available for use as input parameters.

# APPENDIX C

## FNWC SUBSURFACE THERMAL STRUCTURE ANALYSIS

The subsurface temperature analysis is used for the following standard levels: surface, 100 feet, 200 feet, 300 feet, 400 feet, 600 feet, 800 feet, and 1200 feet.

The inputs to the model are: the 12-hour-old temperature analysis at standard levels, climatology at standard levels, sea surface temperature analysis, mixed layer depth analysis, and BT observations for the past 72 hours.

The first step is to prepare guess fields for each standard level. This is done in two steps. First the 12-hour-old analysis is adjusted toward climatology; then this field is adjusted to the sea surface temperature and mixed layer depth analyses to produce the final guess field.

The second step is to prepare data lists from reported observations. Each report is assigned a weight factor on the basis of age and then interpolated to find temperatures at all standard levels from the surface to the bottom of the report.

The final step is to adjust the fields to the data. First the final guess field is adjusted to the data and a light smoothing function is applied to the vertical gradient between the level in question and the level above. This results in a first analysis field. Next, the first

analysis field is adjusted to the data and a vertical control is applied requiring that the temperature at the level in question is less than or equal to the temperature of the level above. The final analysis for a level is produced after the temperature at any level is restricted to the range $-2^{\circ}$C to $35^{\circ}$C.

The primary limitation in this method is the lack of data. In addition, areas of strong currents and areas of strong winds which are not forecast will produce errors in the forecast.

## APPENDIX D

## FNWC HEAT EXCHANGE MODEL

The total heat exchange across the air-sea interface is a combination of five components: heat absorbed from the sun, solar heat reflected from the sea surface, longwave radiation from the sea surface less the incoming longwave radiation from the atmosphere, sensible heat exchange across the air-sea interface, and latent heat exchange thru evaporation or condensation. Each component was calculated from a separate equation and the results were combined to obtain the net heat exchange. Following are the equations used in the computation of each component:

1. Solar insolation, $Q_s$

$$Q_s = 0.014\, A_n t_d (1.0 - 0.0006\, C^3)$$

2. Reflected solar insolation, $Q_r$

$$Q_r = 0.15 Q_s - (0.01 Q_s)^2$$

3. Effective back radiation, $Q_b$

$$Q_b = Q_{ob}(1.0 - 0.765\, C) \qquad \text{where,}$$

$$Q_{ob} = \sigma T_a^4 \left[A + 4\left(\frac{T_w - T_a}{T_a}\right)^2\right] \qquad \text{where,}$$

$$A = 0.261 \exp\left[-7.77 \times 10^{-4} (273 - T_a)\right]$$

4. Latent heat transfer, $Q_e$

$$Q_e = (0.26 + 0.077V)(0.98 e_w - e_a) L_t \qquad [e_w - e_a \quad \text{positive}]$$

$$Q_e = 0.077V(0.98 e_w - e_a) L_t \qquad [e_w - e_a \quad \text{negative}]$$

5. Sensible heat transfer, A

$$Q_h = 39(0.26 + 0.077)(T_w - T_a) \qquad [T_w - T_a \text{ positive}]$$

$$Q_h = 3V(T_w - T_a) \qquad [T_w - T_a \text{ negative}]$$

These five parameters are then combined to give total heat exchange, $Q_n$, as follows:

$$Q_n = Q_s - Q_r - Q_b - Q_e - Q_h \quad .$$

These formulas were selected through a comprehensive literature review and were those which promised the greatest reliability because of performance in studies supported by field testing.

The accuracy of these formulas in synoptic use can be determined directly only in rare instances when a research vessel is available to make radiation measurements. However, it is possible to make an indirect verification by comparing the heat exchange analyses with actual measured changes which occur in the ocean and atmosphere. This type of indirect verification has been used for the past several years, and there has been no evidence that the FNWC heat exchange formulas are inaccurate or in need of change.

The errors which do occur in the heat exchange computations are probably caused by inaccuracies in the input analyses and forecasts. In general, these input parameters are reasonably accurate but errors in meteorological observations and in the manipulating and averaging of sparse data over large sea areas can cause problems. Cloud analyses have been one of the greatest error sources. The wind field analyses are generally good, but a small error in the wind field at

high wind speeds will cause large errors in some heat exchange components, particularly in latent heat exchange.

## APPENDIX E

## FNWC SURFACE CURRENT ANALYSIS

Ocean currents are caused by the combined action of several physical environmental forces. Thermohaline circulation, wind and mass transport by waves, and tidal effects are the most important of these forces. Other forces such as changes in atmospheric pressure, inertia currents, current boundaries, and the coriolis effect were considered, but were discarded for lack of significance or for lack of any forecasting method. Tidal currents are important in coastal waters, and have some magnitude in deep water. However, it was decided that for a 24-hour prediction, the tidal currents could be neglected. The elimination process finally led to the assumption for the model that the total current flow could be described by the vector sum of permanent thermohaline flow and local wind-driven flow, including mass transport by waves.

The thermohaline or permanent circulation evolves from the distribution of ocean temperature and salinity. The thermohaline-type currents have been studied for some 70 years, and have been modeled by geostrophic methods. A drawback in applying this geostrophic method is that it requires accurate information on the distribution of temperature and salinity in the water column for which little real-time salinity data is available. Therefore, the direct

application of the geostrophic method at FNWC has been modified to calculation of a permanent flow component based on the local temperature structure alone.

The permanent component calculation starts by computing a weighted average temperature from the surface to the 600-foot depth. Values for the two levels are taken from FNWC synoptic analyses. Using this average temperature, the thermal wind equation is applied to obtain u and v components of the surface current caused by distribution of sea water temperatures.

The second component in the surface current model is the local wind-driven flow. Complicated calculation methods are available, but they are not well adapted to synoptic analysis so an empirical approach has been used. A simple formula (a constant times the wind speed) was developed relating wind to surface currents. The constant is adjusted to account for mass transport by waves. The wind is computed from the FNWC sea level pressure analysis and the 24-hour sea level pressure forecast. The geostrophic wind is corrected for stability and curvature to obtain a "marine" wind.

Thus, the FNWC total ocean surface current is the vector sum of the thermal and wind-driven components.

The surface current model is designed to produce an accurate picture of current patterns over deep water. It will do this, but it makes no pretense of accuracy in other areas and for all possible

situations. The grid size of about 200 miles precludes accuracy in areas of marked thermal gradients, such as along the edge of strong currents like the Gulf Stream. Very narrow currents can pass between grid points without showing in the surface current analysis. The model does not perform well where for those few currents which are dominated by a haline distribution, as in areas where there is much melting of ice or alternate periods of melting and freezing. A final area of model weakness is in coastal areas or near island chains.

## APPENDIX F

## FNWC SINGULAR ADVECTIVE WAVE AND SWELL MODEL

The total "sea state" may be described as a spectrum of sinusoidal waves of varying frequency and direction of movement.

The singular model typically relates wave height to wind speed through a simple exponential relationship. It is significant to note that singular models usually do not maintain wave continuity from one computational cycle to the next, nor is there provision for energy sinks through dissipation due to opposing winds.

Spectral models treat the growth, propagation and dissipation of energy for a number of frequencies traveling in a number of directions. These models divide the frequency and direction spectrum into a finite set of bands, calculate the changes in energy for each frequency-direction component and integrate over-all components to obtain energy moments which statistically describe the total sea state. More sophisticated spectral models contain wave/wave interaction terms in addition to those relating wind/wave interaction.

Since 180 components are treated at each grid point, spectral models are very demanding on computer time. The singular advective model presently in use represents a compromise between computer limitations and model completeness. It utilizes the propagation of

energy concept but only the frequency of maximum energy is propogated in the direction of the wind. (A single component is selected as being representative of the total spectrum.) Growth and dissipation are achieved through comparison of advective heights with fully developed heights from a new wind field at a later time.

The starting points for each analysis cycle are the six-hour old wind wave and swell fields. The previous wind wave analysis is advected forward in two three-hourly time steps with dissipation and/or growth through comparison with the current wind analysis. The product of these two advective steps is a preliminary calculation of the new wind wave analysis.

A final wind wave analysis is obtained through the introduction of synoptic ship reports into the preliminary calculation of wave heights.

The forecast portion of the model is simply a continuation of the advective propagation outlined above except that forecast winds are used in the dissipation and growth of the wind waves.

The six-hour-old swell trains are similarly advected forward, but without consideration of any interaction with current winds. (This is a weakness which is not inherent to true spectral models where wind/wave and wave/wave interactions occur continually for all frequencies.)

The speed of propagation is proportional to swell period. Since this model makes no provision for the dissipation of swell energy

through swell/wind interaction, swell heights could propagate unchanged. To insure that there will always be some decay in swell heights with time, a decay coefficient has been added to the advective equations.

There are three types of limitations which contribute to inaccuracies in sea/swell analyses and forecasts:

a. Wind errors.

b. Wave observation errors.

c. Modeling limitations.

Even if model formulations were perfect, wind errors would lead to incorrect wave computations. Determination of the wind at the surface of the water which actually controls wave growth is particularly difficult. The forecast winds used in the forecast cycle also contain any errors resulting from deficiencies in the model used to produce the winds.

Wave observation errors also contribute to errors in the final wind wave analysis. This is a significant factor since almost all wave height reports represent an "eyeball" estimate.

The inability of any singular model to define the complete wave energy spectrum and all its interactions is a major modeling limitation. The advective singular model represents a significant improvement over earlier singular approaches for it insures wind wave continuity between runs and treats energy dissipation due to opposing winds. However, wave/wave interactions which influence both growth and dissipation are not considered at all.

## APPENDIX G

## SELECTED BT TRACES

Figures 3 thru 5 show another example of the formation of a shallow surface layer. The difference between this case and the preceding one is that in this example the layer is formed not due to heating but due to wind mixing during a period of slight negative heat exchange. Figure 5 shows the return to a deep layer following a period of substantial negative heat exchange.

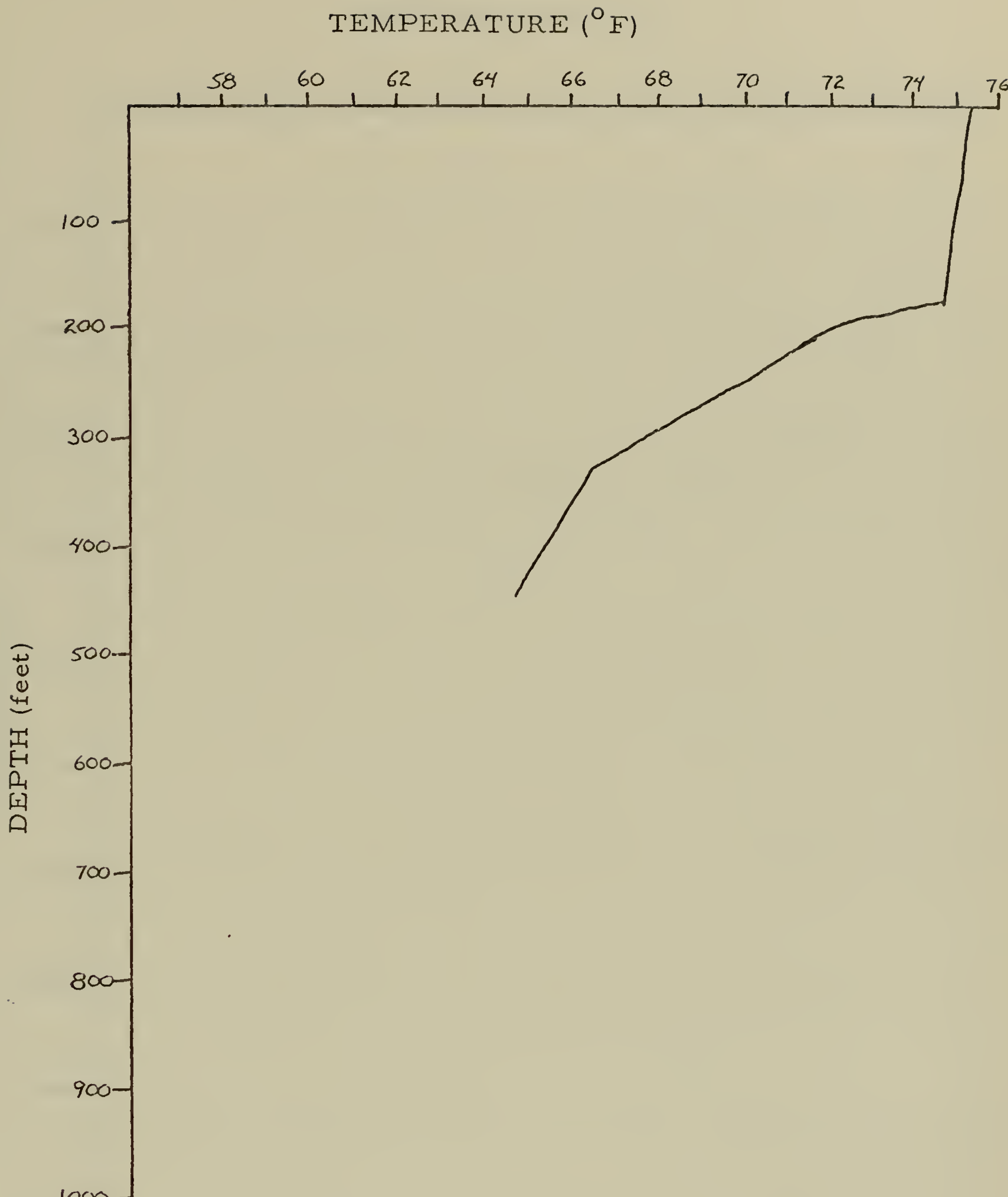



Figure 3. BT trace for 00Z 18 September, Station "N".

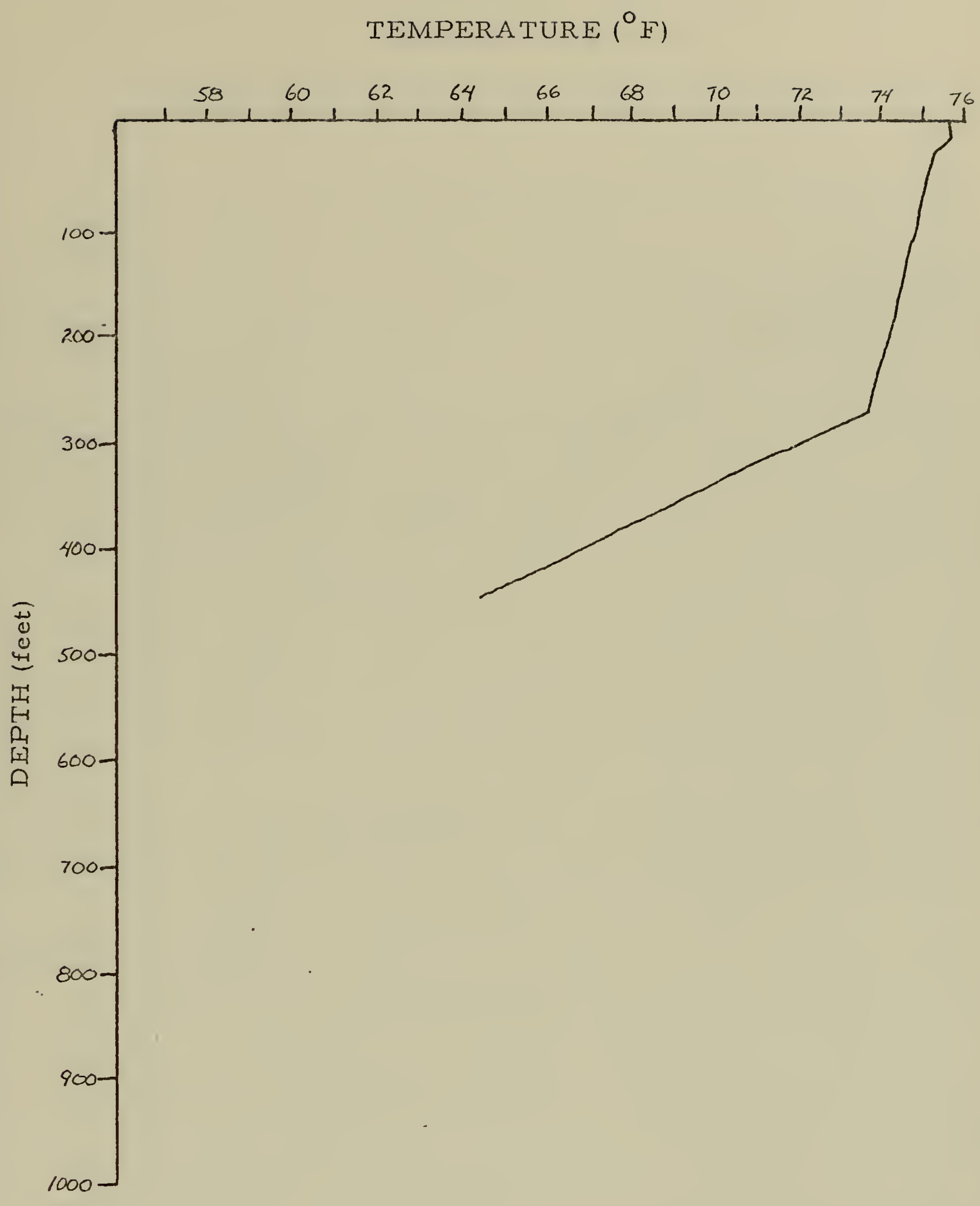



Figure 4. BT trace for 00Z 19 September, Station "N".

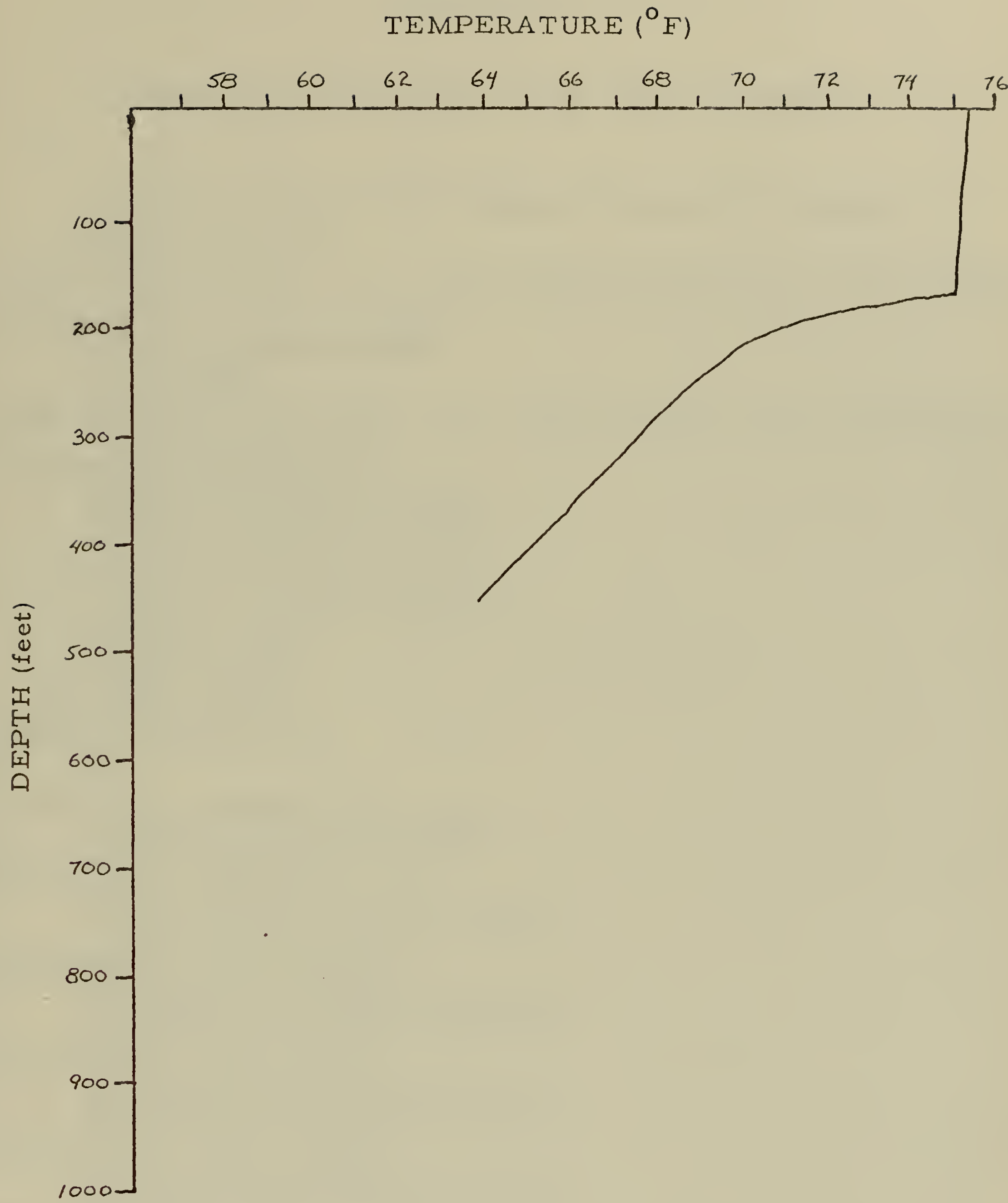



Figure 5. BT trace for 00Z 20 September, Station "N".

APPENDIX H

PROGRAM FOR DAILY MIXED LAYER DEPTH FORECASTS

```
      DIMENSION IT(4),ITS(4),IQN(4),IU(4),IV(4),IWH(4),
      ISH(4),U(4),V(4)
      N=0
      WRITE(6,501)
  501 FORMAT('1',////////,27X,'FORECAST MLD FOR STATION PAPA')
 9000 N=N+1
      IF(N.EQ.9) GO TO 9999
      IF(N.EQ.6) GO TO 5000
      GC TO 5500
 5000 WRITE(6,5001)
 5001 FORMAT('1',////////,27X,'FORECAST MLD FOR STATION PAPA
      (CONT)')
 5500 READ(5,500) KT,KD
      READ(5,1) (IT(I),I=1,4)
      READ(5,1) (ITS(I),I=1,4)
      READ(5,1) (IQN(I),I=1,4)
      READ(5,1) (IU(I),I=1,4)
      READ(5,1) (IV(I),I=1,4)
      READ(5,1) (IWH(I),I=1,4)
      READ(5,1) (ISH(I),I=1,4)
      READ(5,2) PLI
      READ(5,2) RLD
    1 FORMAT (4I6)
    2 FORMAT (F7.2)
  500 FORMAT(2I4)
INTERPOLATION FACTORS     X & Y
      X=
      Y=
INTERPOLATE TEMPERATURE
      TL=IT(1)-X*(IT(1)-IT(2))
      TU=IT(3)-X*(IT(3)-IT(4))
      TF=TU-Y*(TU-TL)
INTERPOLATE TEMPERATURE 600
      TSL=ITS(1)-X*(ITS(1)-ITS(2))
      TSU=ITS(3)-X*(ITS(3)-ITS(4))
      TSF=TSU-Y*(TSU-TSL)
INTERPOLATE HEAT EXCHANGE
      QNL=IQN(1)-X*(IQN(1)-IQN(2))
      QNU=IQN(3)-X*(IQN(3)-IQN(4))
      QNF=QNU-Y*(QNU-QNL)
INTERPOLATE WAVE HEIGHT
      WHL=IWH(1)-X*(IWH(1)-IWH(2))
      WHU=IWH(3)-X*(IWH(3)-IWH(4))
      WHF=WHU-Y*(WHU-WHL)
INTERPOLATE SWELL HEIGHT
      SHL=ISH(1)-X*(ISH(1)-ISH(2))
      SHU=ISH(3)-X*(ISH(3)-ISH(4))
      SHF=SHU-Y*(SHU-SHL)
REDUCE DATA BY SCALING FACTOR
      TC=TF/64.
      TSC=TSF/64.
      T=((9.*TC)+160.)/5.
      TS=((9.*TSC)+160.)/5.
      QN=QNF/16.
      WH=WHF/512.
      SH=SHF/512.
      DO 100 J=1,4
      U(J)=IU(J)/16.
      V(J)=IV(J)/16.
```

```
  100 CONTINUE
      CP=0.935
      RW=1.024
      DCON=0.0
      IF(QN.GE.0.0) GO TO 1200
CONVECTIVE MIXING
      DT=(100.*(T-TS))/(PLI-600.)
      CM=(2.*QN)/(CP*RW*DT)
      DCON=(PLI**2+CM)**0.5
MECHANICAL MIXING
 1200 CH=(WH**2+SH**2)**0.5
      DM=12.5*CH
      IF(DM.GE.DCON) GO TO 1300
      DL=DCON
      GO TO 1000
 1300 DL=DM
CONV/DIV CORRECTION
 1000 A=U(1)+U(3)-U(2)-U(4)+V(3)+V(4)-V(1)-V(2)
GRID SPACING    'G'
      G=
      B=(A*0.864)/(4.*G)
      DD=B*DL
      PRLD=DL+DD
      WRITE(6,502) KT,KD
      WRITE(6,3000) DCON
      WRITE(6,3100) DM
      WRITE(6,3200) DL
      WRITE(6,3300) DD
      WRITE(6,3400) PRLD
      WRITE(6,3500) RLD
  502 FORMAT(' ',////,18X,'FORECAST FOR ',I2,'Z ',I2,' JAN.')
 3000 FORMAT('0',23X,'CONVECTIVE MLD IS ',F8.2)
 3100 FORMAT(' ',23X,'FORCED MLD IS ',F8.2)
 3200 FORMAT(' ',23X,'LAYER DEPTH IS ',F8.2)
 3300 FORMAT(' ',23X,'CONV/DIV CORR IS ',F8.2)
 3400 FORMAT(' ',23X,'FORECAST MLD IS ',F8.2)
 3500 FORMAT(' ',23X,'ACTUAL MLD IS ',F8.2)
      GO TO 9000
 9999 STOP
      END
```

PRCGRAM FOR CONTINUOUS MIXED LAYER DEPTH FORECASTS

```
      DIMENSICN IT(4),ITS(4),IQN(4),IU(4),IV(4),IWH(4),
      ISH(4),U(4),V(4)
      N=0
      WRITE(6,501)
  501 FORMAT('1',////////,22X,'CONTINUCUS MLD FCRECAST FCR
      STATION PAPA')
      READ(5,2) PLI
      PRLD=PLI
 9000 N=N+1
      IF(N.EQ.9) GO TO 9999
      IF(N.EQ.6) GO TO 5000
      GC TO 5500
 50CC WRITE(6,5001)
 5001 FORMAT('1',////////,27X,'FORECAST MLD FOR STATION PAPA
      (CCNT)')
 550C READ(5,50C) KT,KD
      READ(5,1) (IT(I),I=1,4)
      READ(5,1) (ITS(I),I=1,4)
      READ(5,1) (IQN(I),I=1,4)
      READ(5,1) (IU(I),I=1,4)
      READ(5,1) (IV(I),I=1,4)
      READ(5,1) (IWH(I),I=1,4)
      READ(5,1) (ISH(I),I=1,4)
      PLI=PRLD
      READ(5,2) RLD
    1 FCRMAT (4I6)
    2 FORMAT (F7.2)
  500 FCRMAT(2I4)
INTERPCLATICN FACTCRS     X & Y
      X=
      Y=
INTERPOLATE TEMPERATURE
      TL=IT(1)-X*(IT(1)-IT(2))
      TU=IT(3)-X*(IT(3)-IT(4))
      TF=TU-Y*(TU-TL)
INTERPOLATE TEMPERATURE 600
      TSL=ITS(1)-X*(ITS(1)-ITS(2))
      TSL=ITS(3)-X*(ITS(3)-ITS(4))
      TSF=TSU-Y*(TSU-TSL)
INTERPCLATE HEAT EXCHANGE
      QNL=IQN(1)-X*(IQN(1)-IQN(2))
      QNU=IQN(3)-X*(IQN(3)-IQN(4))
      QNF=QNU-Y*(QNU-QNL)
INTERPOLATE WAVE HEIGHT
      WHL=IWH(1)-X*(IWH(1)-IWH(2))
      WHU=IWH(3)-X*(IWH(3)-IWH(4))
      WHF=WHU-Y*(WHU-WHL)
INTERPCLATE SWELL HEIGHT
      SHL=ISH(1)-X*(ISH(1)-ISH(2))
      SHU=ISH(3)-X*(ISH(3)-ISH(4))
      SHF=SHU-Y*(SHU-SHL)
REDUCE DATA BY SCALING FACTOR
      TC=TF/64.
      TSC=TSF/64.
      T=((9.*TC)+160.)/5.
      TS=((9.*TSC)+160.)/5.
      QN=QNF/16.
      WH=WHF/512.
      SH=SHF/512.
      DC 100 J=1,4
      U(J)=IU(J)/16.
      V(J)=IV(J)/16.
  1CC CONTINUE
```

```
      CP=0.935
      RW=1.024
      DCON=0.0
      IF(CN.GE.0.0) GO TO 1200
CONVECTIVE MIXING
      DT=(100.*(T-TS))/(PLI-600.)
      CM=(2.*CN)/(CP*RW*DT)
      DCON=(PLI**2+CM)**0.5
MECHANICAL MIXING
 1200 CH=(WH**2+SH**2)**0.5
      DM=12.5*CH
      IF(DM.GE.DCON) GO TO 1300
      DL=DCON
      GO TO 1000
 1300 DL=DM
CONV/DIV CORRECTION
 1000 A=U(1)+U(3)-U(2)-U(4)+V(3)+V(4)-V(1)-V(2)
GRID SPACING    'G'
      G=
      B=(A*0.864)/(4.*G)
      DD=B*DL
      PRLD=DL+DD
      WRITE(6,502) KT,KD
      WRITE(6,3000) DCON
      WRITE(6,3100) DM
      WRITE(6,3200) DL
      WRITE(6,3300) DD
      WRITE(6,3400) PRLD
      WRITE(6,3500) RLD
  502 FORMAT(' ',////,18X,'FORECAST FOR ',I2,'Z ',I2,' JAN.')
 3000 FORMAT('0',23X,'CONVECTIVE MLD IS ',F8.2)
 3100 FORMAT(' ',23X,'FORCED MLD IS ',F8.2)
 3200 FORMAT(' ',23X,'LAYER DEPTH IS ',F8.2)
 3300 FORMAT(' ',23X,'CONV/DIV CORR IS ',F8.2)
 3400 FORMAT(' ',23X,'FORECAST MLD IS ',F8.2)
 3500 FORMAT(' ',23X,'ACTUAL MLD IS ',F8.2)
      GO TO 9000
 9999 STOP
      END
```

APPENDIX I

FORECAST MLD FOR STATION NOVEMBER

FORECAST FOR 0Z 13 SEP.

```
CONVECTIVE MLD IS       0.0
FORCED MLD IS      53.71
LAYER DEPTH IS      53.71
CONV/DIV CORR IS      -0.37
FORECAST MLD IS      53.34
ACTUAL MLD IS    110.00
```

FORECAST FOR 12Z 13 SEP.

```
CONVECTIVE MLD IS       0.0
FORCED MLD IS      59.25
LAYER DEPTH IS      59.25
CONV/DIV CORR IS      -0.11
FORECAST MLD IS      59.14
ACTUAL MLD IS     60.00
```

FORECAST FOR 0Z 14 SEP.

```
CONVECTIVE MLD IS    110.26
FORCED MLD IS      55.67
LAYER DEPTH IS     110.26
CONV/DIV CORR IS      -0.17
FORECAST MLD IS     110.09
ACTUAL MLD IS    180.00
```

FORECAST FOR 12Z 14 SEP.

```
CONVECTIVE MLD IS     60.21
FORCED MLD IS      55.18
LAYER DEPTH IS      60.21
CONV/DIV CORR IS      -0.11
FORECAST MLD IS      60.10
ACTUAL MLD IS    160.00
```

FORECAST FOR 12Z 15 SEP.

```
CONVECTIVE MLD IS    160.49
FORCED MLD IS      73.91
LAYER DEPTH IS     160.49
CONV/DIV CORR IS       1.09
FORECAST MLD IS     161.58
ACTUAL MLD IS    130.00
```

FORECAST MLD FOR STATION NOVEMBER(CONT)

FORECAST FOR 0Z 16 SEP.

```
CONVECTIVE MLD IS    150.24
FORCED MLD IS    51.32
LAYER DEPTH IS    150.24
CONV/DIV CORR IS      1.11
FORECAST MLD IS    151.35
ACTUAL MLD IS   150.00
```

FORECAST FOR 12Z 16 SEP.

```
CONVECTIVE MLD IS    130.50
FORCED MLD IS    53.70
LAYER DEPTH IS    130.50
CONV/DIV CORR IS      1.01
FORECAST MLD IS    131.51
ACTUAL MLD IS   180.00
```

FORECAST FOR 0Z 19 SEP.

```
CONVECTIVE MLD IS    190.11
FORCED MLD IS    37.08
LAYER DEPTH IS    190.11
CONV/DIV CORR IS      1.03
FORECAST MLD IS    191.14
ACTUAL MLD IS    20.00
```

FORECAST FOR 12Z 19 SEP.

```
CONVECTIVE MLD IS    160.08
FORCED MLD IS    32.67
LAYER DEPTH IS    160.08
CONV/DIV CORR IS      0.11
FORECAST MLD IS    160.19
ACTUAL MLD IS   140.00
```

FORECAST FOR 0Z 20 SEP.

```
CONVECTIVE MLD IS     22.52
FORCED MLD IS    27.62
LAYER DEPTH IS     27.62
CONV/DIV CORR IS      0.21
FORECAST MLD IS     27.83
ACTUAL MLD IS   170.00
```

FORECAST MLD FOR STATION NOVEMBER(CONT)

```
FORECAST FOR 12Z 20 SEP.

        CONVECTIVE MLD IS    140.22
        FORCED MLD IS    29.86
        LAYER DEPTH IS    140.22
        CONV/DIV CORR IS      0.50
        FORECAST MLD IS    140.72
        ACTUAL MLD IS    170.00
```

```
FORECAST MLD FOR STATION NOVEMBER


FORECAST FOR  0Z 12 JAN.

       CONVECTIVE MLD IS    550.06
       FORCED MLD IS   132.37
       LAYER DEPTH IS   550.06
       CONV/DIV CORR IS      1.90
       FORECAST MLD IS   551.96
       ACTUAL MLD IS   530.00


FORECAST FOR 12Z 12 JAN.

       CONVECTIVE MLD IS    560.04
       FORCED MLD IS   125.29
       LAYER DEPTH IS   560.04
       CONV/DIV CORR IS      1.44
       FORECAST MLD IS   561.48
       ACTUAL MLD IS   570.00


FORECAST FOR  0Z 13 JAN.

       CONVECTIVE MLD IS    530.04
       FORCED MLD IS   138.08
       LAYER DEPTH IS   530.04
       CONV/DIV CORR IS      0.76
       FORECAST MLD IS   530.80
       ACTUAL MLD IS   510.00


FORECAST FOR 12Z 13 JAN.

       CONVECTIVE MLD IS    570.02
       FORCED MLD IS    78.65
       LAYER DEPTH IS   570.02
       CONV/DIV CORR IS      1.94
       FORECAST MLD IS   571.95
       ACTUAL MLD IS   530.00
```

FORECAST MLD FOR STATION PAPA

FORECAST FOR 0Z 13 JAN.

```
CONVECTIVE MLD IS    390.15
FORCED MLD IS   164.92
LAYER DEPTH IS   390.15
CONV/DIV CORR IS     10.14
FORECAST MLD IS   400.29
ACTUAL MLD IS   360.00
```

FORECAST FOR 12Z 13 JAN.

```
CONVECTIVE MLD IS      0.0
FORCED MLD IS   130.68
LAYER DEPTH IS   130.68
CONV/DIV CORR IS     -0.88
FORECAST MLD IS   129.80
ACTUAL MLD IS   430.00
```

FORECAST FOR 0Z 19 JAN.

```
CONVECTIVE MLD IS    430.82
FORCED MLD IS   139.04
LAYER DEPTH IS   430.82
CONV/DIV CORR IS      8.90
FORECAST MLD IS   439.72
ACTUAL MLD IS   390.00
```

FORECAST FOR 12Z 19 JAN.

```
CONVECTIVE MLD IS    382.14
FORCED MLD IS   171.10
LAYER DEPTH IS   382.14
CONV/DIV CORR IS      3.53
FORECAST MLD IS   385.67
ACTUAL MLD IS   410.00
```

FORECAST FOR 0Z 20 JAN.

```
CONVECTIVE MLD IS    391.68
FORCED MLD IS   172.31
LAYER DEPTH IS   391.68
CONV/DIV CORR IS     10.94
FORECAST MLD IS   402.63
ACTUAL MLD IS   380.00
```

FORECAST MLD FOR STATION PAPA(CCNT)

FCRECAST FOR 12Z 20 JAN.

```
CONVECTIVE MLD IS    410.00
FORCED MLD IS   134.28
LAYER DEPTH IS   410.00
CONV/DIV CORR IS      9.59
FORECAST MLD IS   419.59
ACTUAL MLD IS   460.00
```

FORECAST MLD FOR STATION ECHO

```
FORECAST FOR  0Z 12 JAN.

      CONVECTIVE MLD IS    898.16
      FORCED MLD IS     83.52
      LAYER DEPTH IS    898.16
      CONV/DIV CORR IS      11.99
      FORECAST MLD IS    910.15
      ACTUAL MLD IS    110.00


FORECAST FOR 12Z 12 JAN.

      CONVECTIVE MLD IS    649.67
      FORCED MLD IS      92.04
      LAYER DEPTH IS    649.67
      CONV/DIV CORR IS      11.13
      FORECAST MLD IS    660.81
      ACTUAL MLD IS    580.00


FORECAST FOR  0Z 15 JAN.

      CONVECTIVE MLD IS    769.89
      FORCED MLD IS      33.51
      LAYER DEPTH IS    769.89
      CONV/DIV CORR IS      -0.14
      FORECAST MLD IS    769.75
      ACTUAL MLD IS    620.00


FORECAST FOR 12Z 15 JAN.

      CONVECTIVE MLD IS    659.92
      FORCED MLD IS      52.49
      LAYER DEPTH IS    659.92
      CONV/DIV CORR IS      18.80
      FORECAST MLD IS    678.72
      ACTUAL MLD IS    650.00


FORECAST FOR  0Z 16 JAN.

      CONVECTIVE MLD IS      0.0
      FORCED MLD IS     45.71
      LAYER DEPTH IS     45.71
      CONV/DIV CORR IS       1.30
      FORECAST MLD IS     47.01
      ACTUAL MLD IS    100.00
```

FORECAST MLD FOR STATICN ECHO(CCNT)

FORECAST FOR 12Z 16 JAN.

```
CCNVECTIVE MLD IS    649.89
FORCED MLD IS    68.38
LAYER DEPTH IS   649.89
CONV/DIV CORR IS     15.86
FORECAST MLD IS   665.75
ACTUAL MLD IS   670.00
```

---

CONTINUOUS MLD FORECAST FOR STATION NOVEMBER

FORECAST FOR 12Z 11 SEP.

```
CONVECTIVE MLD IS       0.0
FORCED MLD IS       39.83
LAYER DEPTH IS       39.83
CONV/DIV CORR IS       -0.73
FORECAST MLD IS       39.10
ACTUAL MLD IS     130.00
```

FORECAST FOR 12Z 12 SEP.

```
CONVECTIVE MLD IS       0.0
FORCED MLD IS       49.13
LAYER DEPTH IS       49.13
CONV/DIV CORR IS       -0.41
FORECAST MLD IS       48.72
ACTUAL MLD IS     160.00
```

FORECAST FOR 12Z 13 SEP.

```
CONVECTIVE MLD IS       0.0
FORCED MLD IS       59.25
LAYER DEPTH IS       59.25
CONV/DIV CORR IS       -0.11
FORECAST MLD IS       59.14
ACTUAL MLD IS      60.00
```

FORECAST FOR 12Z 14 SEP.

```
CONVECTIVE MLD IS      59.36
FORCED MLD IS       55.18
LAYER DEPTH IS       59.36
CONV/DIV CORR IS       -0.11
FORECAST MLD IS       59.25
ACTUAL MLD IS     160.00
```

FORECAST FOR 12Z 15 SEP.

```
CONVECTIVE MLD IS      60.86
FORCED MLD IS       73.91
LAYER DEPTH IS       73.91
CONV/DIV CORR IS        0.50
FORECAST MLD IS       74.41
ACTUAL MLD IS     130.00
```

FORECAST MLD FOR STATION NOVEMBER(CONT)

FORECAST FOR 12Z 16 SEP.

```
CONVECTIVE MLD IS      75.38
FORCED MLD IS     53.70
LAYER DEPTH IS     75.38
CONV/DIV CORR IS       0.58
FORECAST MLD IS     75.97
ACTUAL MLD IS    180.00
```

**********************************************************************************************************************
**********************************************************************************************************************
**********************************************************************************************************************

CONTINUCUS MLD FCRECAST FCR STATION NOVEMBER

FORECAST FCR 0Z 11 SEP.

CCNVECTIVE MLD IS 0.0
FCRCED MLC IS 29.02
LAYER DEPTH IS 29.02
CONV/DIV CORR IS -0.44
FORECAST MLD IS 28.57
ACTUAL MLD IS 160.00

FCRECAST FCR 0Z 12 SEP.

CONVECTIVE MLD IS 0.0
FORCED MLD IS 18.86
LAYER DEPTH IS 18.86
CONV/DIV CORR IS -0.20
FORECAST MLD IS 18.66
ACTUAL MLD IS 120.00

FORECAST FOR 0Z 13 SEP.

CCNVECTIVE MLD IS 0.0
FORCED MLD IS 53.71
LAYER DEPTH IS 53.71
CONV/DIV CORR IS -0.37
FORECAST MLD IS 53.34
ACTUAL MLD IS 110.00

FCRECAST FCR 0Z 14 SEP.

CONVECTIVE MLD IS 53.93
FORCED MLD IS 55.67
LAYER DEPTH IS 55.67
CONV/DIV CORR IS -0.09
FCRECAST MLD IS 55.59
ACTUAL MLD IS 180.00

***********************************************************************
***********************************************************************
***********************************************************************

CONTINUOUS MLD FORECAST FOR STATICN NCVEMBER

FORECAST FCR 0Z 12 JAN.

```
CONVECTIVE MLD IS    550.06
FORCED MLD IS   132.37
LAYER DEPTH IS   550.06
CONV/DIV CORR IS      1.90
FORECAST MLD IS    551.96
ACTUAL MLD IS   530.00
```

FORECAST FOR 0Z 13 JAN.

```
CONVECTIVE MLD IS    551.99
FORCED MLD IS   138.08
LAYER DEPTH IS   551.99
CONV/DIV CORR IS      0.79
FORECAST MLD IS    552.78
ACTUAL MLD IS   510.00
```

FORECAST FCR 0Z 14 JAN.

```
CONVECTIVE MLD IS    552.81
FORCED MLD IS    83.18
LAYER DEPTH IS   552.81
CONV/DIV CORR IS      1.61
FORECAST MLD IS    554.42
ACTUAL MLD IS   520.00
```

FORECAST FOR 0Z 15 JAN.

```
CONVECTIVE MLD IS      0.0
FORCED MLD IS    42.45
LAYER DEPTH IS    42.45
CONV/DIV CORR IS      0.33
FORECAST MLD IS     42.78
ACTUAL MLD IS   540.00
```

FORECAST FCR 0Z 16 JAN.

```
CONVECTIVE MLD IS     45.77
FORCED MLD IS    82.02
LAYER DEPTH IS    82.02
CONV/DIV CORR IS     -0.23
FORECAST MLD IS     81.79
ACTUAL MLD IS   440.00
```

FORECAST MLD FOR STATION NOVEMBER(CONT)

```
FORECAST FOR  0Z 17 JAN.

      CONVECTIVE MLD IS     84.14
      FORCED MLD IS   114.14
      LAYER DEPTH IS   114.14
      CONV/DIV CORR IS      C.44
      FORECAST MLD IS    114.58
      ACTUAL MLD IS   540.00


FORECAST FOR  0Z 18 JAN.

      CONVECTIVE MLD IS      0.0
      FORCED MLD IS    46.32
      LAYER DEPTH IS    46.32
      CONV/DIV CORR IS     -0.57
      FORECAST MLD IS    45.75
      ACTUAL MLD IS   520.00


FORECAST FOR  0Z 19 JAN.

      CONVECTIVE MLD IS     46.17
      FORCED MLD IS    77.63
      LAYER DEPTH IS    77.63
      CONV/DIV CORR IS     -0.29
      FORECAST MLD IS    77.35
      ACTUAL MLD IS   500.00


FORECAST FOR  0Z 20 JAN.

      CONVECTIVE MLD IS     77.62
      FORCED MLD IS    87.75
      LAYER DEPTH IS    87.75
      CONV/DIV CORR IS     -0.26
      FORECAST MLD IS    87.48
      ACTUAL MLD IS   590.00
```

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CONTINUOUS MLD FORECAST FOR STATION PAPA

```
FORECAST FOR  0Z 13 JAN.

        CONVECTIVE MLD IS    390.15
        FORCED MLD IS   164.92
        LAYER DEPTH IS   390.15
        CONV/DIV CORR IS     10.14
        FORECAST MLD IS   400.29
        ACTUAL MLD IS   360.00


FORECAST FOR  0Z 14 JAN.

        CONVECTIVE MLD IS      0.0
        FORCED MLD IS   231.18
        LAYER DEPTH IS   231.18
        CONV/DIV CORR IS      1.57
        FORECAST MLD IS   232.75
        ACTUAL MLD IS  9999.00


FORECAST FOR  0Z 15 JAN.

        CONVECTIVE MLD IS      0.0
        FORCED MLD IS   332.13
        LAYER DEPTH IS   332.13
        CONV/DIV CORR IS      4.07
        FORECAST MLD IS   336.20
        ACTUAL MLD IS  9999.00


FORECAST FOR  0Z 16 JAN.

        CONVECTIVE MLD IS   337.39
        FORCED MLD IS   211.43
        LAYER DEPTH IS   337.39
        CONV/DIV CORR IS     -1.25
        FORECAST MLD IS   336.14
        ACTUAL MLD IS   330.00


FORECAST FOR  0Z 17 JAN.

        CONVECTIVE MLD IS   338.42
        FORCED MLD IS   204.18
        LAYER DEPTH IS   338.42
        CONV/DIV CORR IS      1.04
        FORECAST MLD IS   339.46
        ACTUAL MLD IS  9999.00
```

FORECAST MLD FOR STATION PAPA(CONT)

FORECAST FOR 0Z 18 JAN.

```
CONVECTIVE MLD IS    341.38
FORCED MLD IS   192.08
LAYER DEPTH IS   341.38
CONV/DIV CORR IS      6.54
FORECAST MLD IS   347.92
ACTUAL MLD IS   430.00
```

FORECAST FOR 0Z 19 JAN.

```
CONVECTIVE MLD IS    349.43
FORCED MLD IS    139.04
LAYER DEPTH IS   349.43
CONV/DIV CORR IS      7.22
FORECAST MLD IS   356.65
ACTUAL MLD IS   390.00
```

FORECAST FOR 0Z 20 JAN.

```
CONVECTIVE MLD IS    358.78
FORCED MLD IS   172.31
LAYER DEPTH IS   358.78
CONV/DIV CORR IS     10.02
FORECAST MLD IS   368.80
ACTUAL MLD IS   380.00
```

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A theoretical model is developed for making computerized forecasts of mixed layer depth. An empirical equation relating significant wave height to layer depth is used to account for mechanical mixing. Heat exchange parameters are introduced into the model to produce convective mixing. The u and v components of surface current are used to investigate the effect of convergence and divergence. The layer depths forecast by the

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model are compared to actual layer depths and to the Fleet Numerical Weather Central layer depth analysis.

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An investigation of various parameters which may affect the mixed layer depth in the ocean.